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EXPERIMENTS ON CARBON FIBRE REINFORCED PLASTIC TUBES IN TORSION--ETC(U)
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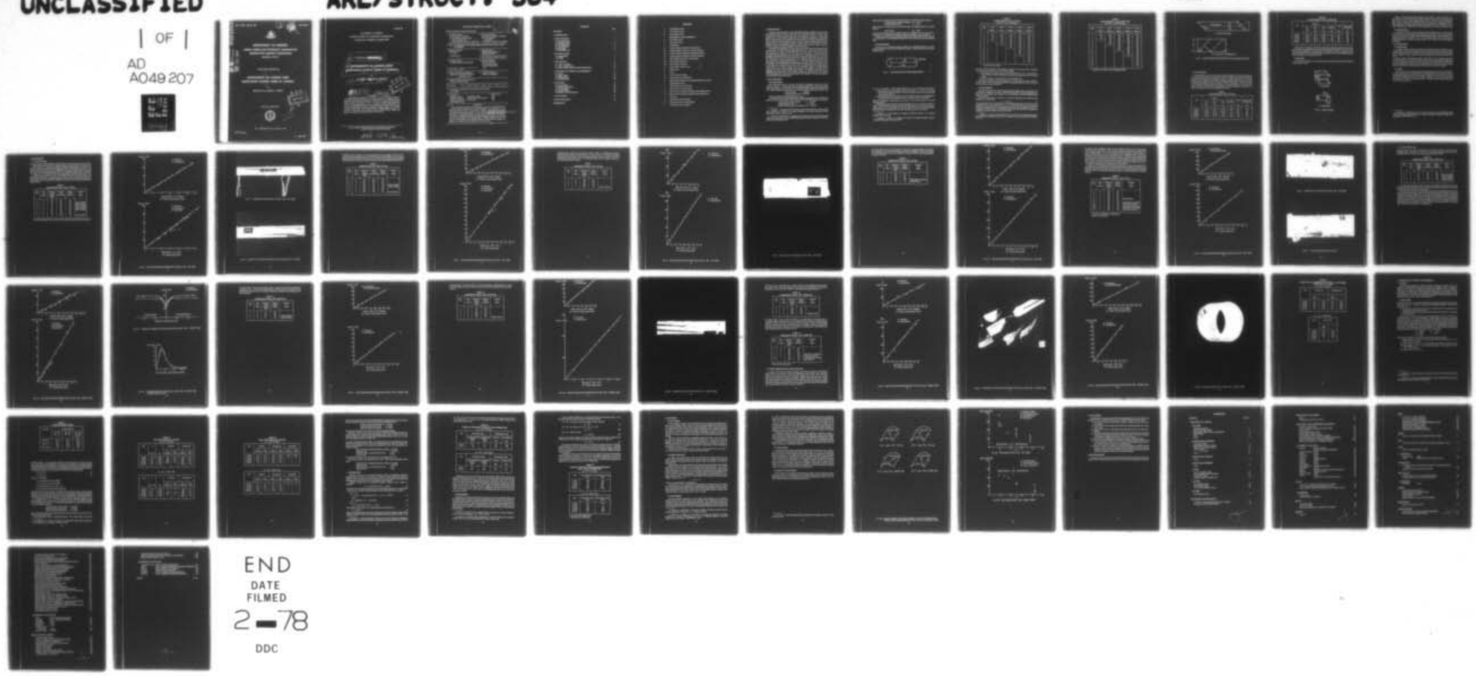

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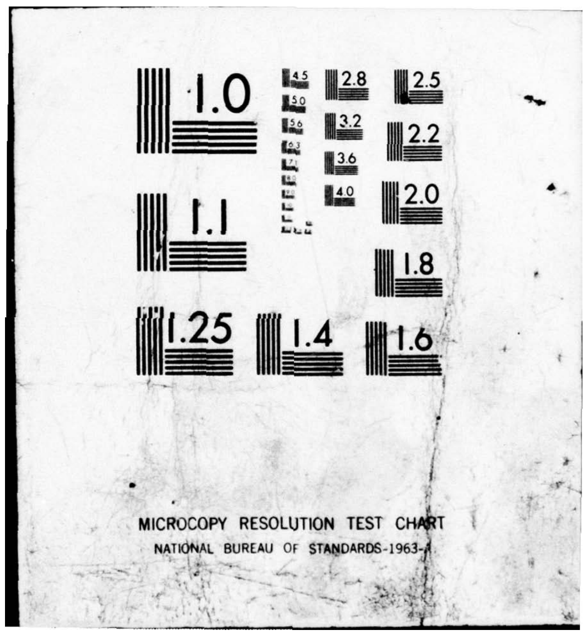
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MELBOURNE, VICTORIA

STRUCTURES REPORT 364

EXPERIMENTS ON CARBON FIBRE REINFORCED PLASTIC TUBES IN TORSION

by

ROBIN ELLIS and BRIAN C. HOSKIN

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6 **EXPERIMENTS ON CARBON FIBRE REINFORCED PLASTIC TUBES IN TORSION,**

by

10 ROBIN ELLIS [redacted] BRIAN C. HOSKIN

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SUMMARY

An experimental programme has been carried out on the torsional properties of carbon fibre reinforced plastic tubes. Two laminate patterns were investigated: the first had equal numbers of layers with the fibres at +45° and −45°, whilst the second had equal numbers of layers with the fibres at +30°, −30° and 90°, all angles being measured with respect to a longitudinal generator of a tube. The tubes had various wall thicknesses, the thinner ones being designed to fail by torsional buckling and the thicker ones to undergo a material strength failure. For the buckling failures, a significant difference was observed between the critical values of the torque for clockwise and anti-clockwise loadings: this difference was related to the fibre directions in the outer layer.

POSTAL ADDRESS: Chief Superintendent, Aeronautical Research Laboratories,
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CONTENTS

NOTATION

d	mean diameter of tube
d_i	inner diameter of tube
d_o	outer diameter of tube
l	gauge length for rotation measurements
r_i	inner radius of tube
r_o	outer radius of tube
t	wall thickness
E_1	Young's modulus of basic ply in fibre direction
E_2	Young's modulus of basic ply in transverse direction
E_L	Young's modulus of laminate in longitudinal direction
E_T	Young's modulus of laminate in transverse direction
F_{1t}	tensile strength of basic ply in fibre direction
G_{12}	shear modulus of basic ply
G_{LT}	shear modulus of laminate
I_p	polar moment of inertia of tube
L	length of tube
T	torque
T_b	critical torque for buckling
T_m	critical torque for material failure
α	angle between fibre direction and longitudinal generator of tube
γ	engineering shear strain
ν_1	major Poisson's ratio for basic ply
ν_2	minor Poisson's ratio for basic ply
ν_L	Poisson's ratio for laminate associated with longitudinal stress
ν_T	Poisson's ratio for laminate associated with transverse stress
τ	shear stress
τ_b	critical shear stress for buckling
τ_m	critical shear stress for material failure
θ	total angle of twist over length l.

1. INTRODUCTION

Structural components made in high performance composite materials, such as carbon fibre reinforced plastic (CFRP) and boron fibre reinforced plastic (BFRP) are already being incorporated in aircraft, and their future use can be expected to increase. In order to gain experience both in the theoretical design and in the experimental evaluation of components made in these materials, a test programme has been carried out on CFRP torque tubes. This type of specimen was chosen partly because it is a basic structural element, partly because it afforded a chance of investigating two modes of failure (namely, torsional buckling for thin-walled tubes and a material strength failure for thicker ones), and partly because a procedure for tube manufacture had been developed in these Laboratories.

An account of an investigation on torque tubes made in glass fibre reinforced plastic (GFRP) has been given by Cervelli[1] and the present programme was, to some extent, based on that work. (See, also, the work by Cole and Cervelli[2].) Two series of tubes were made: in the first, the laminate pattern comprised $+45°/-45°$ layers and, in the second, $+30°/-30°/90°$ layers, the angles being measured between the fibre direction and a longitudinal generator of the tube. The former pattern is the one usually chosen for an element transmitting a pure shear since, then, the fibres are oriented in the directions of the equivalent tension and compression. The latter pattern was also investigated because the work of Cervelli indicated that it gave a better performance in the buckling regime for GFRP tubes; this pattern yields an isotropic laminate. All the tubes were of circular cross-section and 381 mm long (between end fittings) with an inside diameter of 25·4 mm; however, their wall thicknesses ranged from approximately 0·6 mm to 3·4 mm. As already indicated, the thin tubes were designed to undergo torsional buckling and the thick ones a material strength failure. An additional feature that was investigated for the thin tubes was the increase in strength that resulted when a tube was filled with a lightweight foam. Along with the question of the strength of the tubes, investigations were also made of their elastic moduli.

2. TEST SPECIMENS

2.1 Fibre-Resin System

The carbon fibre used for the tubes was "Hyfil 27" obtained in the form of sheets 1220 mm × 390 mm × 0·13 mm, each sheet comprising prealigned fibres which had been sized with a small quantity of DX 210 epoxy resin. This particular carbon fibre is usually characterised as a "medium strength, medium modulus" one; material properties quoted by the supplier were

Young's modulus = 202 GPa
Ultimate tensile strength = 2200 MPa

The matrix material was Shell 828/DDS epoxy resin.

From tensile tests on flat laminate specimens, with all fibres parallel, made in this fibre-resin system, and with a measured fibre volume fraction of 67%, the following data were obtained:

Young's modulus in fibre direction, $E_1 = 134$ GPa
associated Poisson's ratio, $\nu_1 = 0{\cdot}30$
ultimate tensile strength in fibre direction, $F_{1t} = 1120$ MPa

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1. Cervelli, R. V. Strength of Thick Wall Glass Filament Wound Tubes for Aircraft Landing Gear Application, pp. 369–434 of "Testing Techniques for Filament Reinforced Plastics Symposium" AFML-TR-66-274, 1967.

2. Cole, B. W. and Cervelli, R. V. Comparison of Composite and Non-Composite Structural Tubes. AIAA Paper 68-340, AIAA/ASME 9th Structures, Structural Dynamics and Materials Conference, Palm Springs, 1968.

(These values were obtained from tests where the tension was applied in the fibre direction.)

Young's modulus in transverse direction, $E_2 = 10$ GPa
associated Poisson's ratio, $\nu_2 = 0{\cdot}02$

(These values were obtained from tests where the tension was applied transverse to the fibre direction)

shear modulus, $G_{12} = 6$ GPa

(This value was obtained from tests where the tension was applied at 45° to the fibre direction, although this is not regarded as a satisfactory way for determining the shear modulus.)

The above provided the design data for the basic ply to be used in the torque tubes although it was realised that it was questionable whether a 67% fibre volume fraction would be achieved there.

2.2 Laminate Patterns

The axis used for specifying the laminate patterns was a longitudinal generator of a tube; the fibre orientation in any layer was defined by the angle, α, between a generator and the fibre direction (Fig. 1).

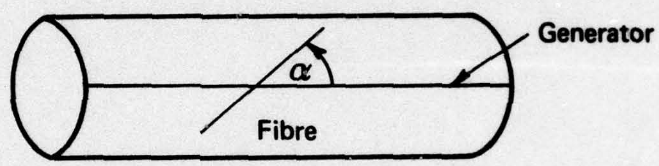

FIG. 1. CONVENTION FOR FIBRE ORIENTATION

(a) *+45°/−45° Laminates:*—The desirable conditions for a +45°/−45° laminate were as follows:

(i) there should be an equal number of layers having fibres at +45° and −45° so that the laminate would be orthotropic with its axes of elastic symmetry in the longitudinal and transverse directions,

(ii) the lay-ups should be symmetric about the mid-thickness plane so that bending effects associated with the heterogeneous nature of a laminate would be minimised[3, 4].

However, for laminates comprising only a few layers it is not always possible to meet both these requirements.

The laminate patterns adopted for tubes comprising 4, 6, 8, 12 or 16 layers are shown in Table 1. Of these, all but the 6-layer one meet both requirements. For this tube, both requirements cannot be met; inadvertently this tube was made to satisfy the second requirement, rather than the more important first one. Thus, the 6-layer tube was not orthotropic.

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3. Calcote, L. R. The Analysis of Laminated Composite Structures. Van Nostrand Reinhold, New York, 1969.

4. Ashton, J. E., Halpin, J. C. and Petit, R. H. Primer on Composite Materials: Analysis. Technomic Publishing Co., Stamford, 1969.

TABLE 1

Laminate Patterns for $+45°/-45°$ Tubes

(Layer No. 1 is the inside layer)

Layer No.	4-Layers α (degrees)	6-Layers* α (degrees)	8-Layers α (degrees)	12-Layers α (degrees)	16-Layers α (degrees)
1	+45	+45	+45	+45	+45
2	−45	−45	−45	−45	−45
3	−45	+45	+45	+45	+45
4	+45	+45	−45	−45	−45
5		−45	−45	+45	+45
6		+45	+45	−45	−45
7			−45	−45	+45
8			+45	+45	−45
9				−45	−45
10				+45	+45
11				−45	−45
12				+45	+45
13					−45
14					+45
15					−45
16					+45

* Non-orthotropic laminate.

(*b*) $+30°/-30°/90°$ *Laminates:*—The desirable conditions for the second series of laminates were of essentially the same nature as for the first, namely,

(i) there should be an equal number of layers having fibres at $+30°$, $-30°$ and $90°$ so that the laminate would be orthotropic; in this case it is actually isotropic (for in-plane loads),

(ii) the lay-up should be symmetric about the mid-thickness plane.

The patterns adopted for tubes comprising 3, 6, 9, 12 and 18 layers are shown in Table 2. Of these, the 6, 12 and 18 layer patterns satisfy both requirements but the 3 and 9 layer ones do not satisfy the second requirement.

2.3 Tube Manufacture

The tubes were made by a sheet-wrapping process developed on-site. An account of this has been given elsewhere[5], but, briefly, it involved wrapping strips of pre-impregnated fibres by hand on to an aluminium alloy mandrel of 25·4 mm diameter, and then consolidating and curing the material.

In order to add a layer of orientation, α, to a partly constructed tube of current outside diameter, d_c, a strip of width

$$w = \pi\, d_c \cos \alpha \tag{1}$$

was cut and then wrapped spiral-fashion on to the existing tube (Fig. 2). (For the case of a nominally 90° layer, a very narrow strip ($w = 3 \cdot 1$ mm) was used; this led to an actual fibre orientation of approximately 88°.) By proceeding in the above way the length of the tube was completely covered with a layer of CFRP where the fibres were continuous and of the appropriate orientation. For further details, see the reference cited.

5. Baker, A. A., Ellis, R. and Hutchison, M. M. Construction of an Experimental Carbon Fibre Reinforced Plastic Bipod Leg for an 81 mm Mortar Unit. ARL Report Met. 95/SM351, Oct. 1974.

TABLE 2

Laminate Patterns for +30°/−30°/90° Tubes

(Layer No. 1 is the inside layer)

Layer No.	3-Layers* α (degrees)	6-Layers α (degrees)	9-Layers* α (degrees)	12-Layers α (degrees)	18-Layers α (degrees)
1	+30	+30	+30	+30	+30
2	90	−30	−30	−30	−30
3	−30	90	90	90	90
4		90	+30	+30	+30
5		−30	90	−30	−30
6		+30	−30	90	90
7			90	90	+30
8			−30	−30	−30
9			+30	+30	90
10				90	90
11				−30	−30
12				+30	+30
13					90
14					−30
15					+30
16					90
17					−30
18					+30

* Laminate not symmetric about mid-thickness plane.

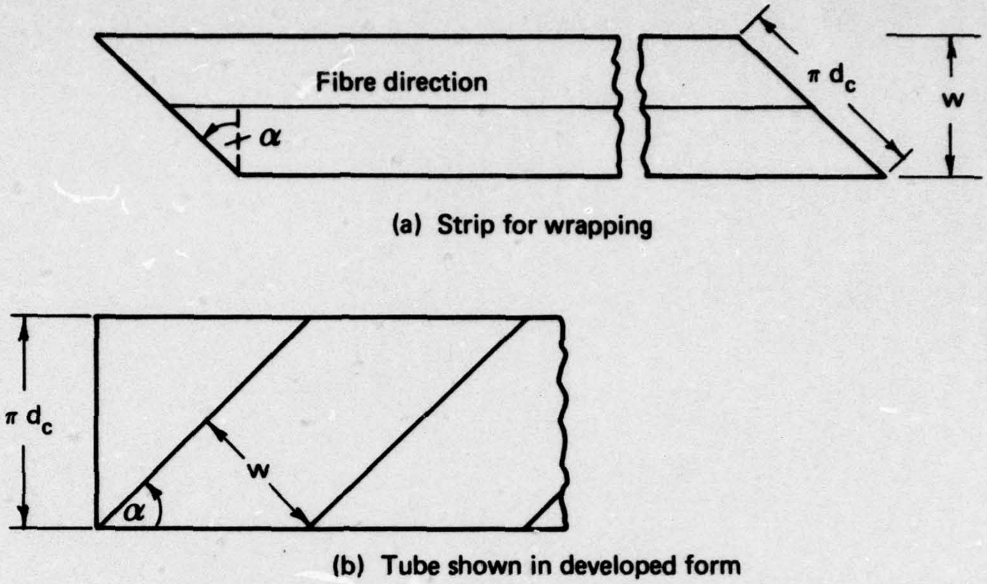


FIG. 2. SHEET WRAPPING PROCEDURE FOR TUBE MANUFACTURE

2.4 Tube Dimensions

Geometrical data for the two sets of tubes are given in Tables 3 and 4. The inside diameter was, of course, governed by the mandrel size. The outside diameter measurement is given for a station half-way along the tube; typically, there was a variation of around 2% in the outside diameter over the length of the tube although sometimes a larger variation occurred. As actually manufactured, the length of each tube was around 500 mm; the length, L, cited in the Tables is the unsupported length between end fittings i.e., the working length of a tube under test. The last column in the Tables gives the gauge length over which measurements of rotation were made i.e., the length over which a measured twist occurred.

TABLE 3
Geometrical Data for +45°/−45° Tubes

Tube	Diameter			Wall Thickness	Length	Gauge Length for Rotation
	Inner d_i (mm)	Outer d_o (mm)	Mean d (mm)	t (mm)	L (mm)	l (mm)
4-Layer	25·40	26·78	26·09	0·69	381	362
6-Layer	25·40	27·67	26·54	1·14	381	372
8-Layer	25·40	28·57	26·99	1·59	381	363
12-Layer	25·40	30·06	27·73	2·33	381	360
16-Layer	25·40	31·45	28·43	3·03	381	361

TABLE 4

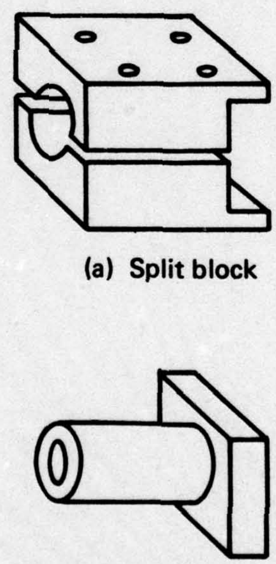
Geometrical Data for +30°/−30°/90° Tubes

Tube	Diameter			Wall Thickness	Length	Gauge Length for Rotation
	Inner d_i (mm)	Outer d_o (mm)	Mean d (mm)	t (mm)	L (mm)	l (mm)
3-Layer	25·40	26·63	26·02	0·62	381	349
6-Layer	25·40	27·53	26·47	1·07	381	363
9-Layer	25·40	28·39	26·90	1·50	381	359
12-Layer	25·40	29·50	27·45	2·05	381	356
18-Layer	25·40	32·13	28·77	3·37	381	356

The thickness of a single layer of CFRP as obtained by averaging over all tubes is 0·186 mm. The thickness of a single layer in the flat specimens referred to in Section 2.1 was 0·14 mm and the corresponding fibre volume fraction was measured to be 67%. Assuming that the increased thickness per layer in the tubes is due to extra resin, the fibre volume fraction achieved there would appear to be approximately 50%.

2.5 End Fittings

The torque was applied to a tube through square steel end fittings, the general arrangement being as shown in Fig. 3.



(a) Split block

(b) Insert piece

FIG. 3. END FITTINGS

Using a room temperature setting araldite two part adhesive, a tube was bonded on its outer surface to the split block and on its inner surface to the insert piece; the length of the glue line was 50·8 mm. A trial short-length 16-layer $+45°/-45°$ tube—which was expected to be as strong as the strongest specimen in the main programme—was successfully tested to failure using these end fittings; this tube failed at a torque of 1333 Nm. Unfortunately, as will be seen, difficulties due to glue failures in the end fittings did arise at torques well below this value.

2.6 Foam-Filled Tubes

It transpired that those tubes that failed by torsional buckling did so in a purely elastic fashion, the tubes recovering entirely on unloading. In such cases a tube was then removed from the test machine and completely filled with expanded polyurethane foam. Tubes that were foam-filled were the 4- and 6-layer $+45°/-45°$ ones and the 3-layer $+30°/-30°/90°$ one. (An unsuccessful attempt was made to foam-fill the 6-layer $+30°/-30°/90°$ tube, the foam solidifying prematurely).

3. TEST PROCEDURE

3.1 Instrumentation

An angular measuring system was attached near each end of a tube so that the twist over a gauge length, l, that was only slightly less than the tube length, could be measured. Values of l have already been given in Tables 3 and 4. The measurements of twist were used in calculating the shear modulus of a tube; generally they were only taken over the lower part of the torque range.

Electric resistance strain gauges (typically, TML FCA 6-23, 120 Ω gauges attached with M-Bond 200 adhesive plus catalyst) were used to measure shear strains. The main gauge station was at the mid-point of a tube, on its outer surface. The strain measurements were used to provide an independent estimate of the shear modulus and, also, to confirm the onset of buckling; this last revealed itself in departures from linearity in the plot of torque versus strain.

3.2 Loading

The tubes were loaded by a mechanical torsion testing machine with a capacity of 2260 Nm. It was discovered in the test programme that the buckling strength of a given tube could vary substantially depending on the sense of the torque; a reference to this has since been found in the literature[6]. Simply for the purpose of making a distinction, the two senses of the torque are referred to as "clockwise" and "anticlockwise"; a correlation with a structural characteristic of a tube will be given later.

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6. Marlowe, D. E., Sushinsky, G. F. and Dexter, H. B. Elastic Torsional Buckling of Thin-Walled Composite Cylinders pp. 84–108 of "Composite Materials: Testing and Design (Third Conference)", ASTM STP 546, 1974.

4. TEST RESULTS

4.1 +45°/−45° Tubes

(a) *4-Layer Tube:*—The full schedule of tests carried out on this one tube is shown in Table 5.

The main points are that, for a clockwise loading, the tube buckled at a (mean) torque of 48 Nm whilst, for an anticlockwise loading, the (mean) buckling torque was 74 Nm. In all cases the buckling was elastic, the tube regaining its shape on unloading. When the tube was filled with foam it sustained a torque of 96 Nm before undergoing a material failure. The weight of the tube (over its working length) when empty was 31 g and the weight of foam used was 22 g.

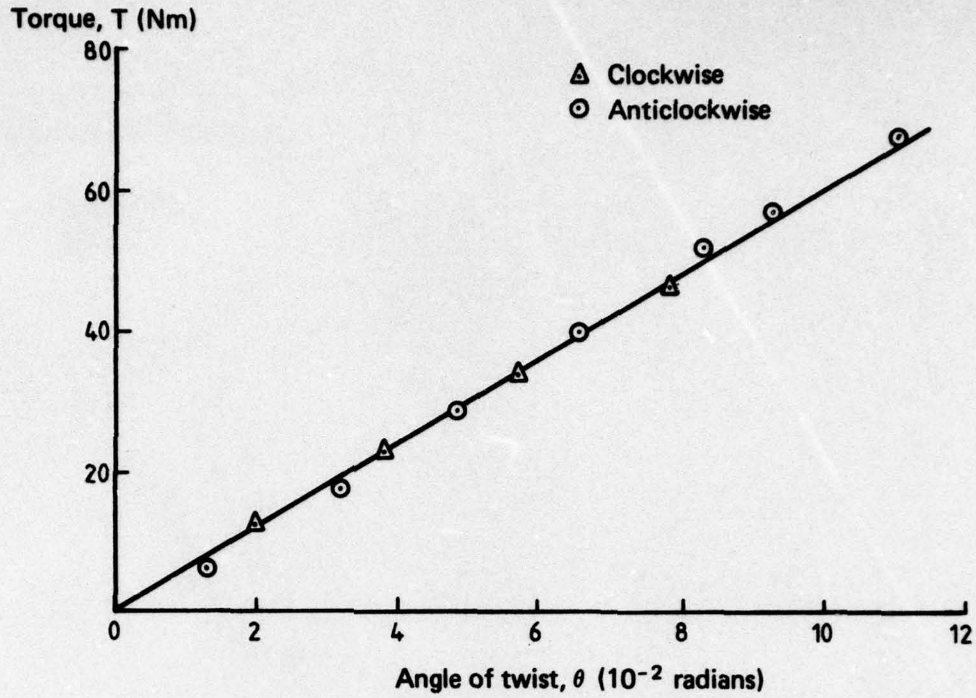
Typical plots of the angle of twist over the gauge length l, and of the shear strain at the central station as functions of torque are shown in Fig. 4. It will be noted that the strain plot is markedly non-linear near the buckling torque but that the plot is virtually linear right up to failure when the tube is foam-filled. A buckled tube is shown in Fig. 5 and the final material failure in Fig. 6.

TABLE 5

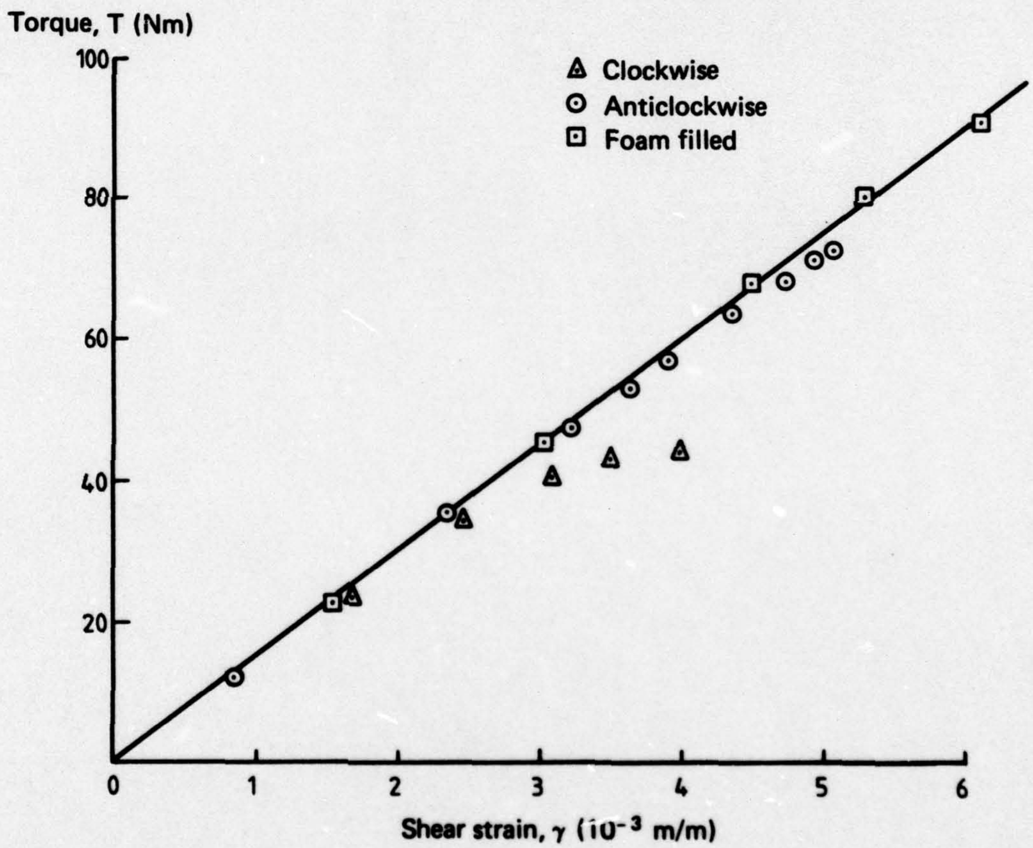
Loading Runs for 4 Layer +45°/−45° Tube

Run No.	Sense of Torque*	Maximum Torque Applied (Nm)	Whether Tube Foam-Filled	Whether Failure Occurred	Comments on Failure
1	A	68	No	No	
2	C	50	No	Yes	Elastic buckling
3	C	50	No	Yes	Elastic buckling
4	A	75	No	Yes	Elastic buckling
5	A	72	No	Yes	Elastic buckling
6	C	44	No	Yes	Elastic buckling
7	C	81	Yes	No	
8	A	89	Yes	No	
9	C	96	Yes	Yes	Material failure

* In this and subsequent Tables, C and A stand for clockwise and anti-clockwise respectively



(a) Torque vs (total) angle of twist



(b) Torque vs shear strain

FIG. 4. DEFLECTIONS AND STRAINS FOR 4-LAYER + 45°/– 45° TUBE

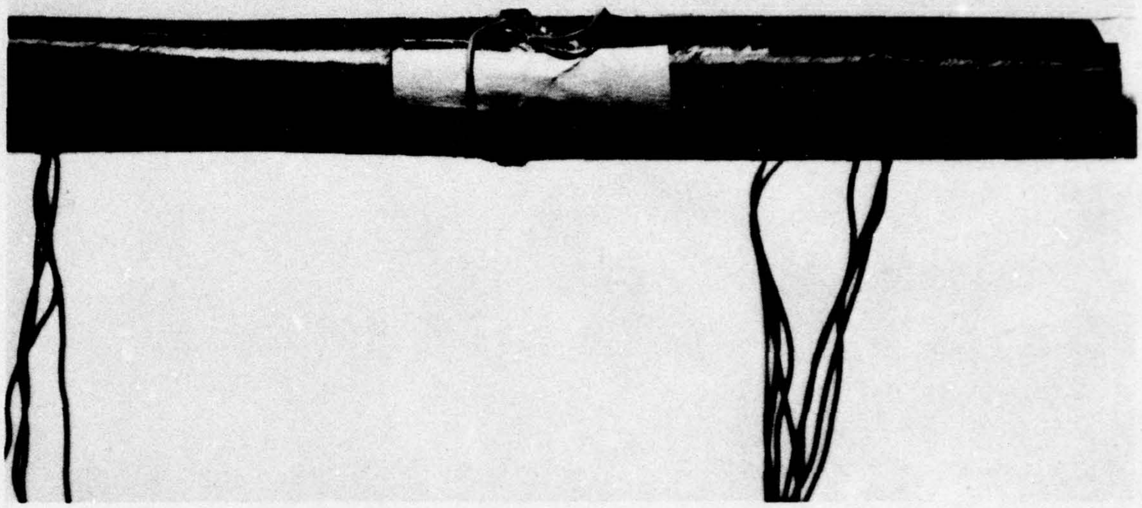


FIG. 5. TORSIONAL BUCKLING OF 4-LAYER + 45°/– 45° TUBE

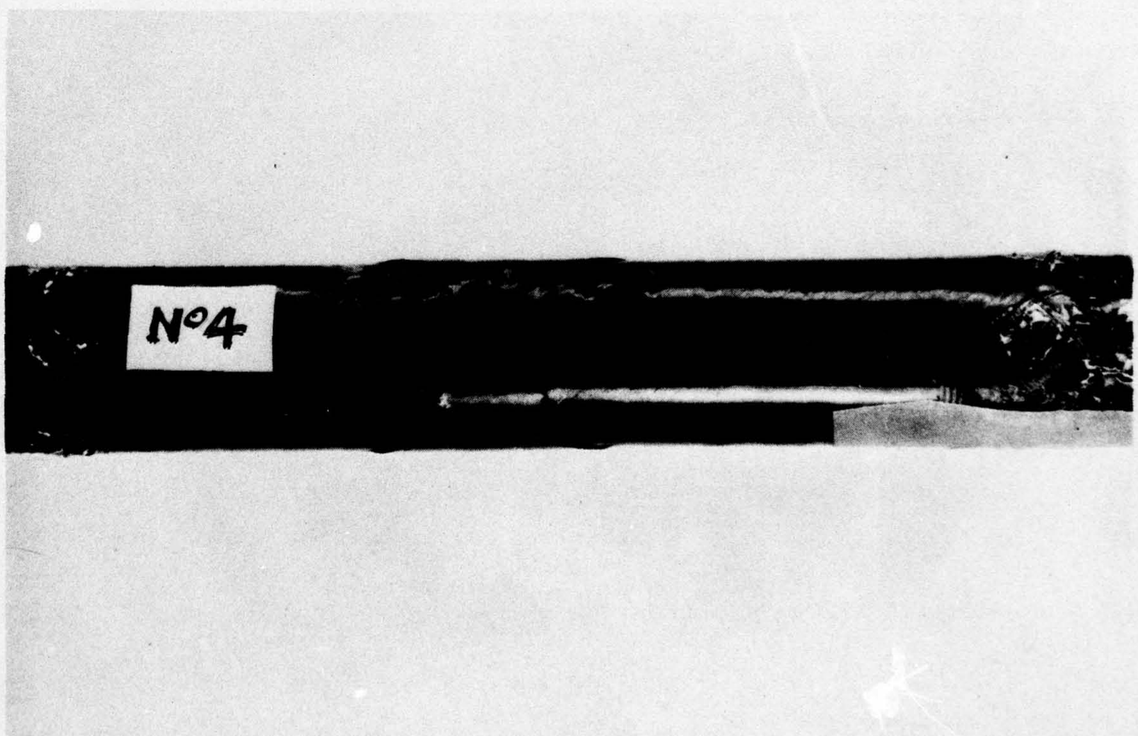


FIG. 6. MATERIAL FAILURE OF FOAM FILLED 4-LAYER + 45°/– 45° TUBE

(b) *6-Layer Tube:*—The tests on this (non-orthotropic) tube are detailed in Table 6. For a clockwise torque buckling occurred at 149 Nm and for an anti-clockwise torque at 200 Nm; when the tube was foam-filled it sustained a torque of 262 Nm before suffering a material failure (of the same character as the previous tube). Twist and strain measurements are shown in Fig. 7.

TABLE 6

Loading Runs for 6-Layer +45°/−45° Tube

Run No.	Sense of Torque	Maximum Torque Applied (Nm)	Whether Tube Foam-Filled	Whether Failure Occurred	Comments on Failure
1	A	68	No	No	
2	C	102	No	No	
3	A	147	No	No	
4	C	149	No	Yes	Elastic buckling
5	A	200	No	Yes	Elastic buckling
6	C	215	Yes	No	
7	A	226	Yes	No	
8	C	262	Yes	Yes	Material failure

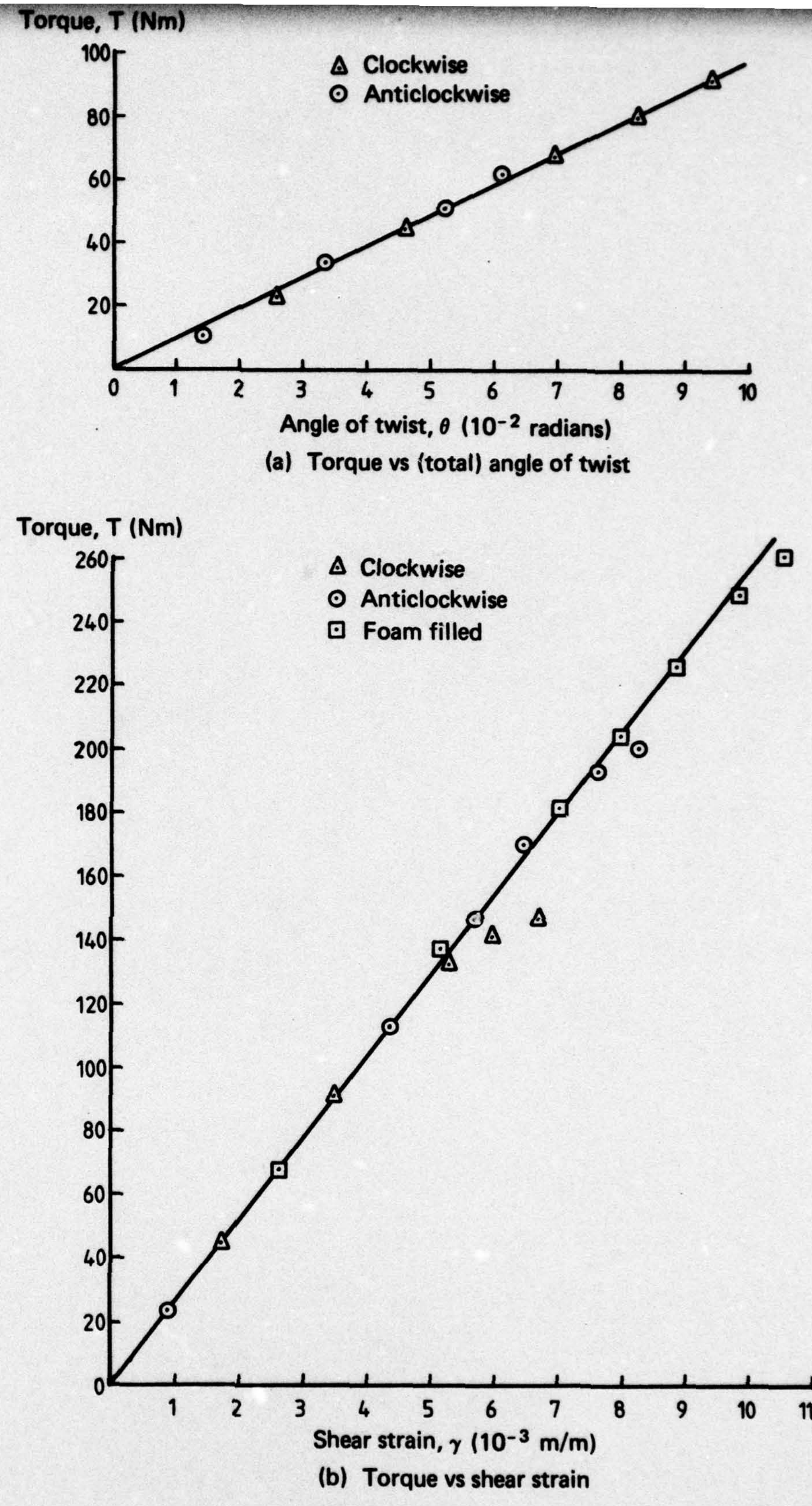


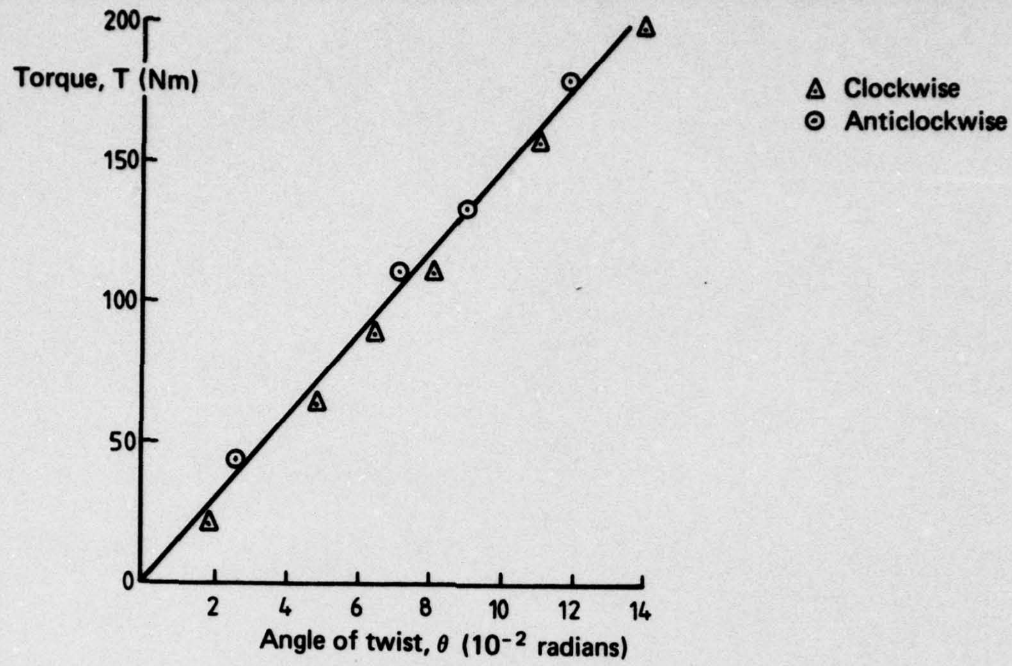
FIG. 7. DEFLECTIONS AND STRAINS FOR 6-LAYER + 45°/– 45° TUBE

(c) *8-Layer Tube:*—The tests on this tube are listed in Table 7. No buckling was observed; instead the tube underwent a material failure at a torque of 294 Nm. The absence of buckling is confirmed by the linearity of the strain gauge results (Fig. 8) up to the failure torque. The failed specimen itself is shown in Fig. 9. A considerable degree of fibre "waviness" can be seen; this was present before the failure.

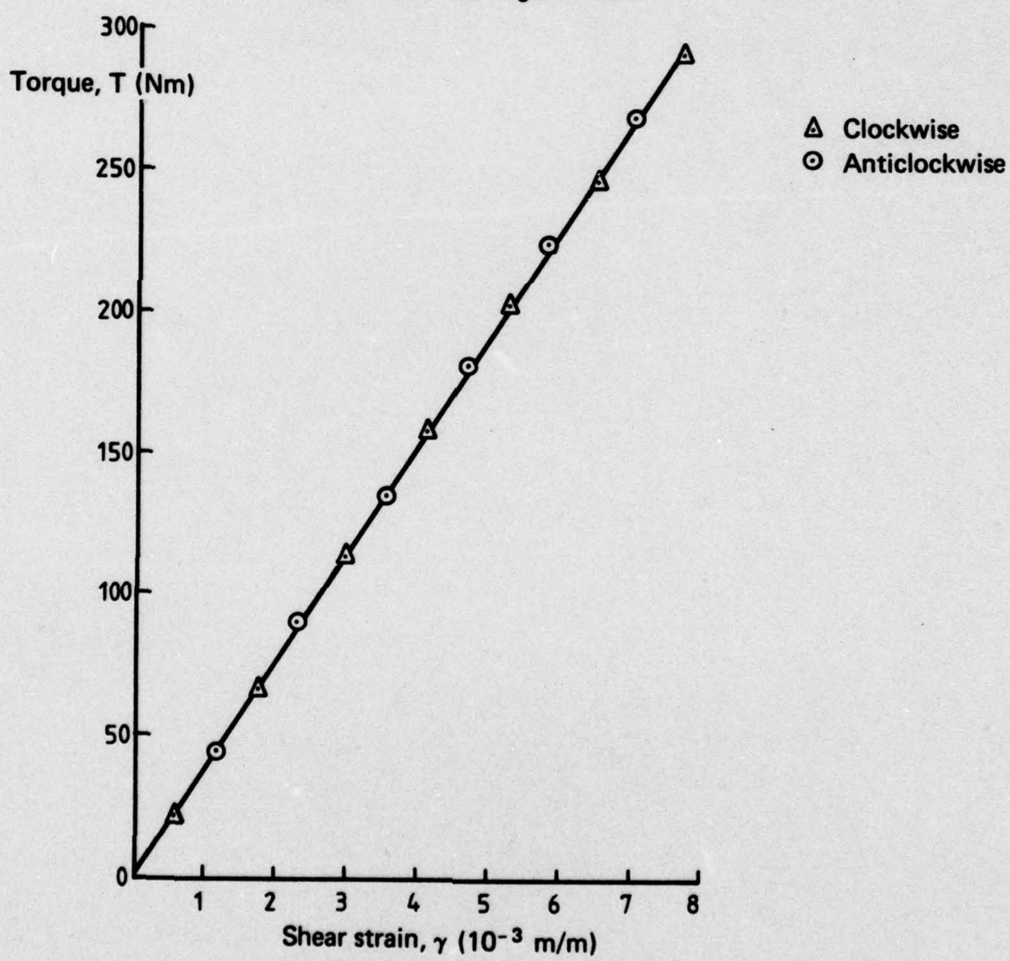
TABLE 7

Loading Runs for 8-Layer +45°/−45° Tube

Run No.	Sense of Torque	Maximum Torque Applied (Nm)	Whether Failure Occurred	Comments on Failure
1	A	181	No	
2	C	226	No	
3	A	226	No	
4	C	294	No	
5	A	294	Yes	Material failure



(a) Torque vs (total) angle of twist



(b) Torque vs shear strain

FIG. 8. DEFLECTIONS AND STRAINS FOR 8-LAYER + 45°/– 45° TUBE

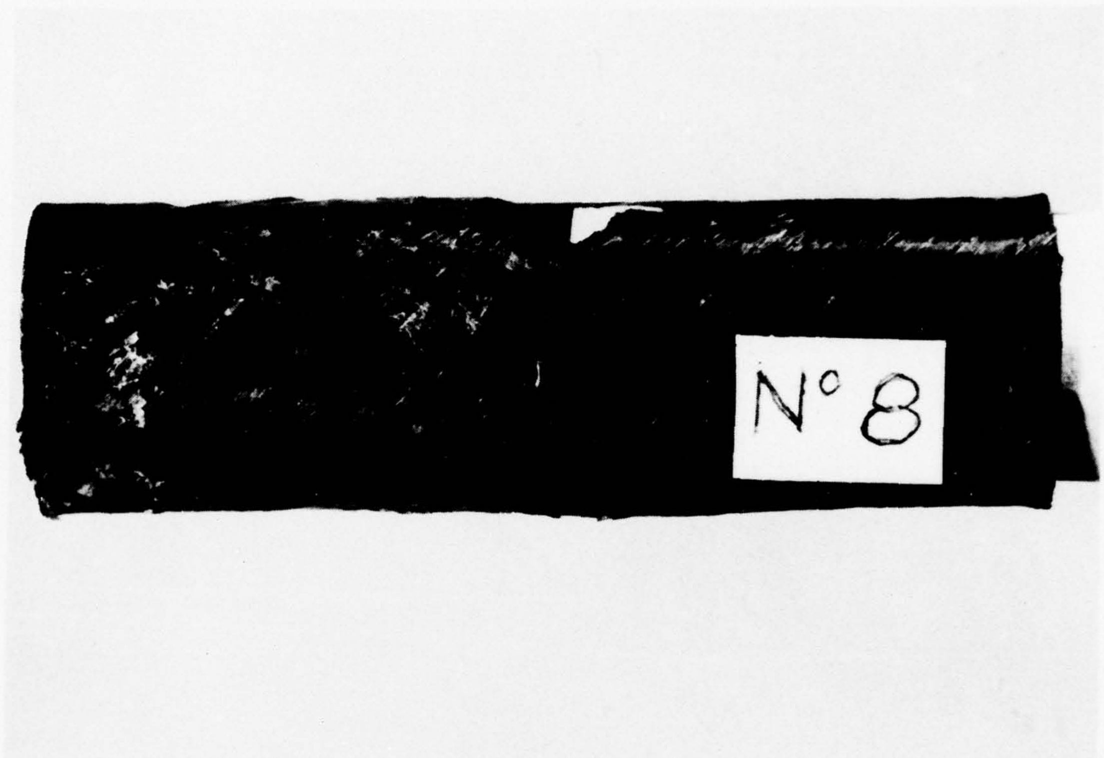


FIG. 9. MATERIAL FAILURE OF 8-LAYER + 45°/– 45° TUBE

(d) *12-Layer Tube:* Five test runs were made on this tube as detailed in Table 8. On the fourth run a glue failure occurred in the end fitting at a torque of only 588 Nm. The joint was re-glued and a material failure in the tube was achieved at a torque of 675 Nm. Twist and strain data are shown in Fig. 10.

TABLE 8

Loading Runs for 12-Layer $+45°/-45°$ Tube

Run No.	Sense of Torque	Maximum Torque Applied (Nm)	Whether Failure Occurred	Comments on Failure
1	A	363	No	
2	C	452	No	
3	A	534	No	
4	C	588	Yes	Glue failure in end fitting
5	A	675	Yes	Material failure

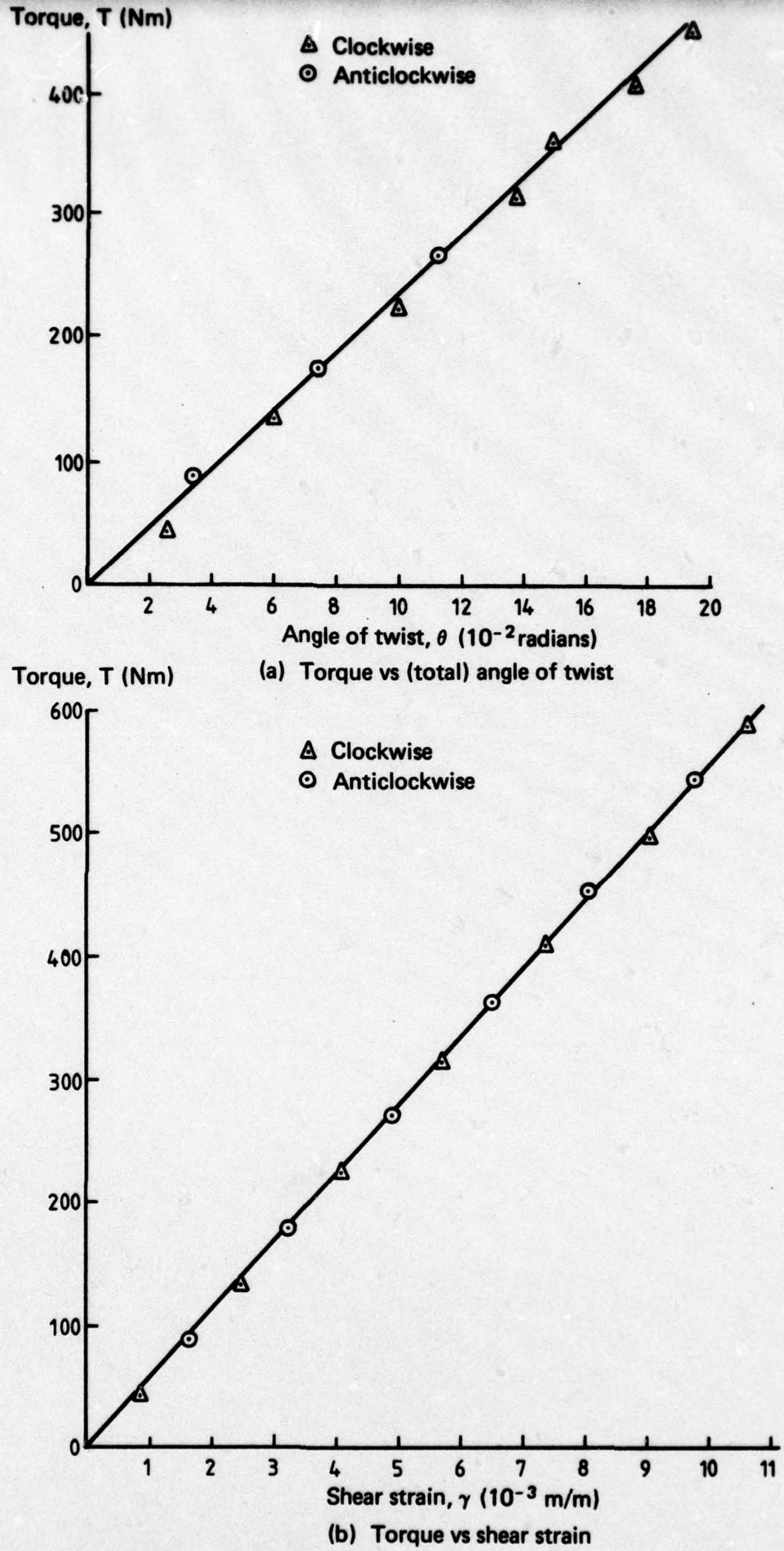


FIG. 10. DEFLECTIONS AND STRAINS FOR 12-LAYER + 45°/– 45° TUBE

(e) *16-Layer Tube:*—Satisfactory results were not obtained with this tube. The full schedule of tests is given in Table 9 and it will be noted that after tests at relatively low torques, where the twist measurements of Fig. 11 were obtained, the tube underwent a material failure at a torque of 845 Nm (Fig. 12). (This was unexpected since, as mentioned earlier, a trial tube of basically the same cross-section had sustained a torque of over 1300 Nm.) A shortened specimen was prepared from the failed tube in an attempt to obtain a second tube failure; however, this was not achieved. Instead, a glue failure occurred in the end fittings at a torque of 792 Nm and then, when the end was re-glued and drive pins inserted through the fittings into the tube, a material failure originated at the pin-holes at a torque of 724 Nm.

Because of the apparently poor performance of this tube, a second one of essentially the same dimensions was manufactured. No valid specimen failure was achieved with this, a series of failures occurring in the end fittings (Runs 9, 10 and 11). The maximum torque reached was 950 Nm in Run 11; here drive pins were again being used and failure originated at a pin-hole (Fig. 13).

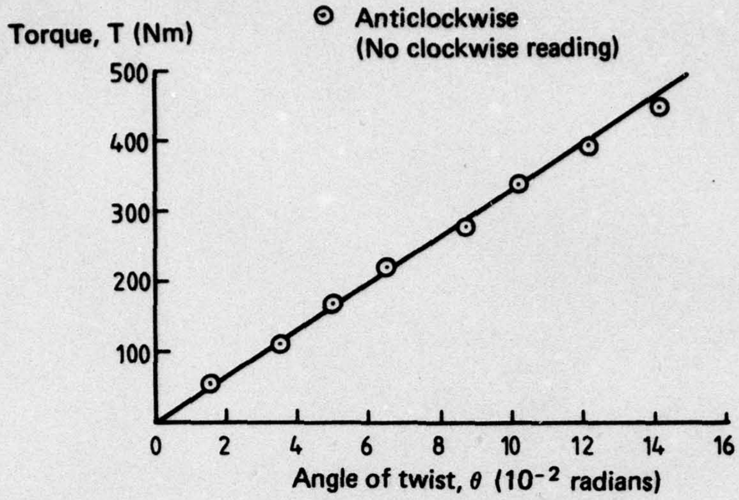
TABLE 9

Loading Runs for 16-Layer +45°−45° Tube

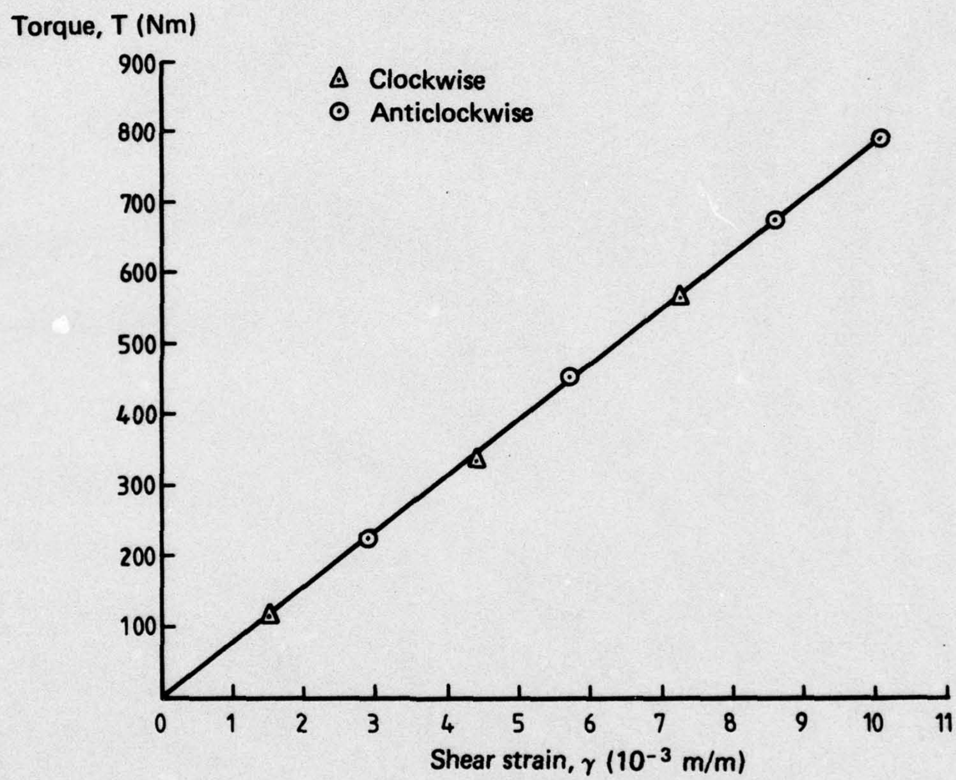
Run No.	Sense of Torque	Maximum Torque Applied (Nm)	Whether Failure Occurred	Comments on Failure
1	A	226	No	
2	C	226	No	
3	A	452	No	
4	C	679	No	
5	A	845	Yes	Material failure
6*	A	679	No	
7*	C	792	Yes	Glue failure in end fitting
8*	A	724	Yes	Failure from pin-hole
9**	C	927	Yes	Glue failure in end fitting
10**	C	803	Yes	Glue failure in end fitting
11**	A	950	Yes	Failure from pin-hole

* Runs on shortened length of original tube.

** Runs on a second tube.



(a) Torque vs (total) angle of twist



(b) Torque vs shear strain

FIG. 11. DEFLECTIONS AND STRAINS FOR 16-LAYER + 45°/– 45° TUBE

FIG. 12. MATERIAL FAILURE OF 16-LAYER + 45°/-- 45° TUBE

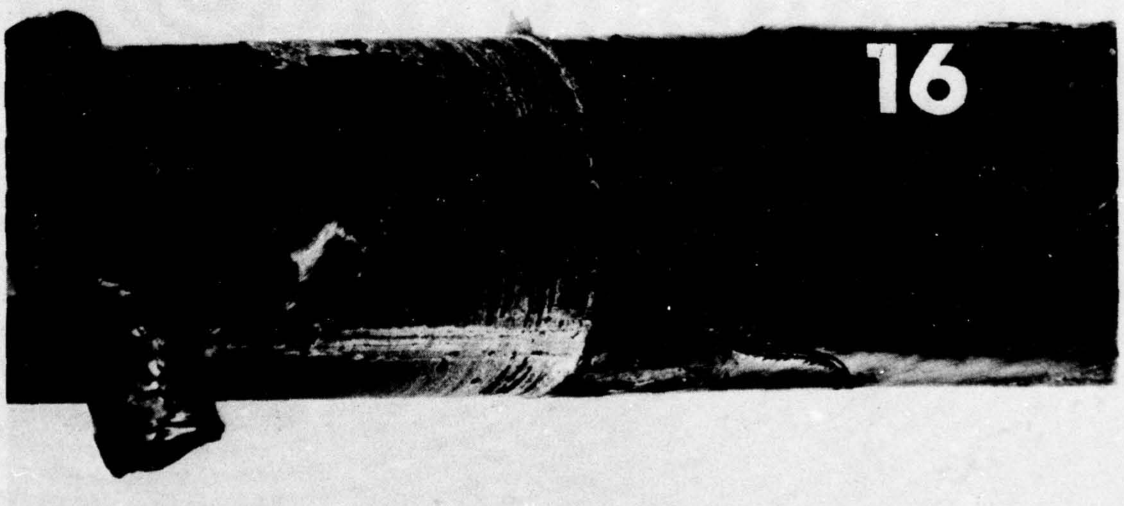


FIG. 13. FAILURE FROM DRIVE PIN HOLE

4.2 +30°/−30°/90° Tubes

(a) *3-Layer Tube:*—The five runs carried out on this tube are shown in Table 10. Elastic buckling occurred at torques of 21·5 Nm in the anticlockwise direction and 25 Nm in the clockwise direction. Twist and strain measurements are shown in Fig. 14.

TABLE 10

Loading Runs for 3-Layer +30°/−30°/90° Tube

Run No.	Sense of Torque	Maximum Torque Applied (Nm)	Whether Tube Foam-Filled	Whether Failure Occurred	Comments on Failure
1	A	20	No	No	
2	C	25	No	Yes	Elastic buckling
3	A	21·5	No	Yes	Elastic buckling
4	C	25	No	Yes	Elastic buckling
5	A	70·5	Yes	Yes	Material failure

For this tube, measurements were also made on the changes in diameter in the vicinity of the buckling load; the marked increase in the horizontal diameter and decrease in the vertical diameter at the same station are shown in Fig. 15.

This tube was also tested when foam-filled and, here, the foam-filling process itself was looked at in a little more detail. In Fig. 16 is shown the circumferential strain that was developed in the tube during the foaming; it can be seen that the strain reached a maximum value about 6 minutes after pouring of the foam into the tube had commenced and that it had decayed virtually to zero after about 30 minutes. The weight of foam used was 22 g whilst the weight of the tube itself (over the 381 mm working length) was 25 g. In the foam-filled condition the tube underwent a material failure at a torque of 70·5 Nm; the linear character of the strains (Fig. 14) showed that buckling had been suppressed.

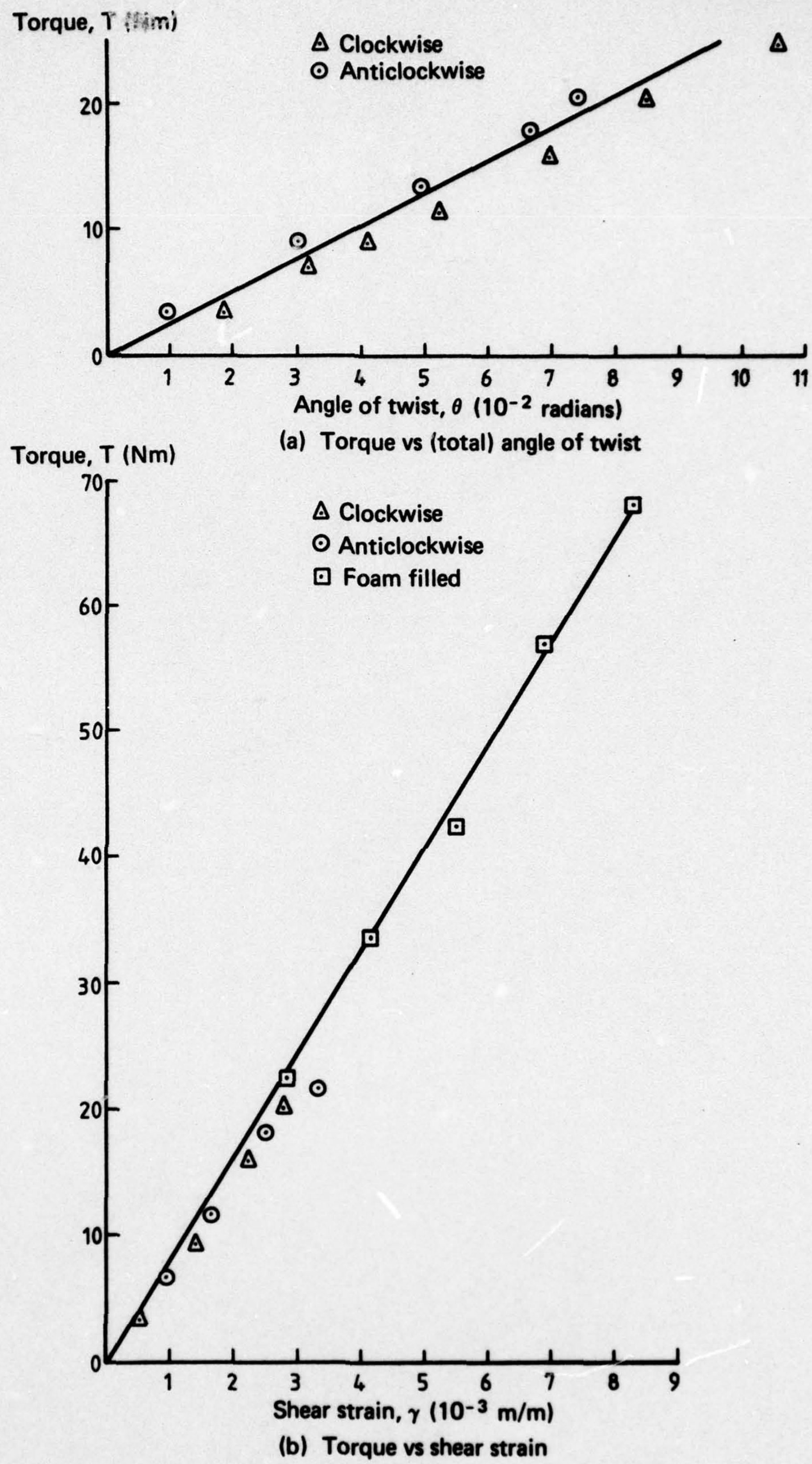


FIG. 14. DEFLECTIONS AND STRAINS FOR 3-LAYER + 30°/– 30°/90° TUBE

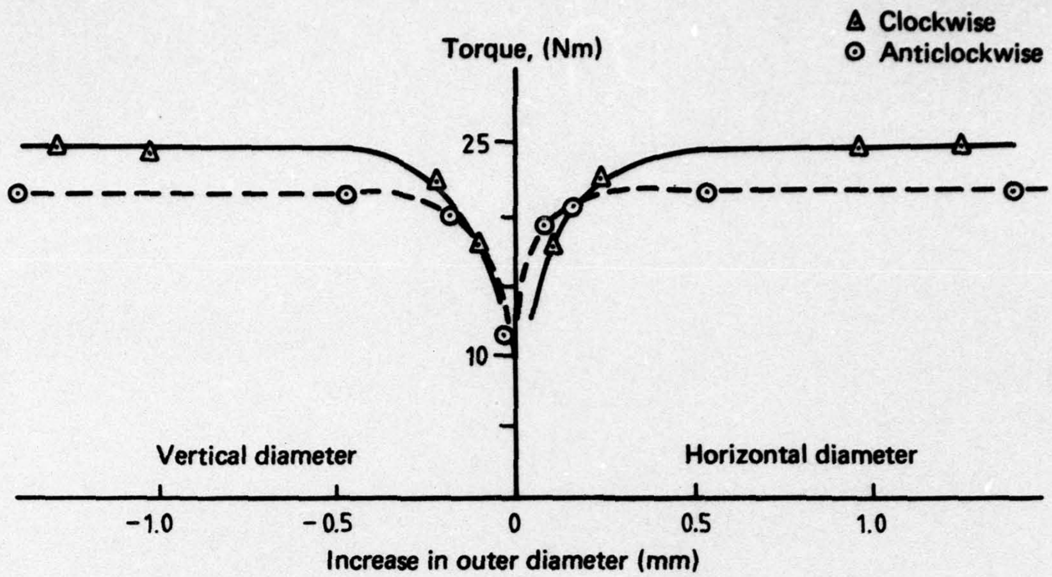


FIG. 15. CHANGE IN DIAMETER AT BUCKLING FOR 3-LAYER + 30°/ – 30°/90° TUBE

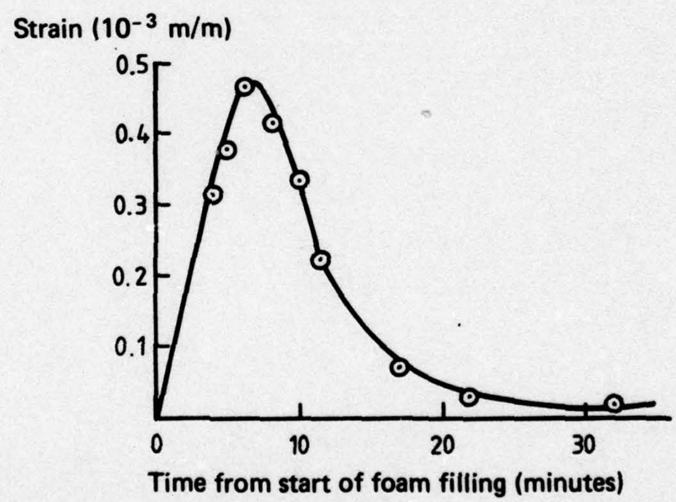


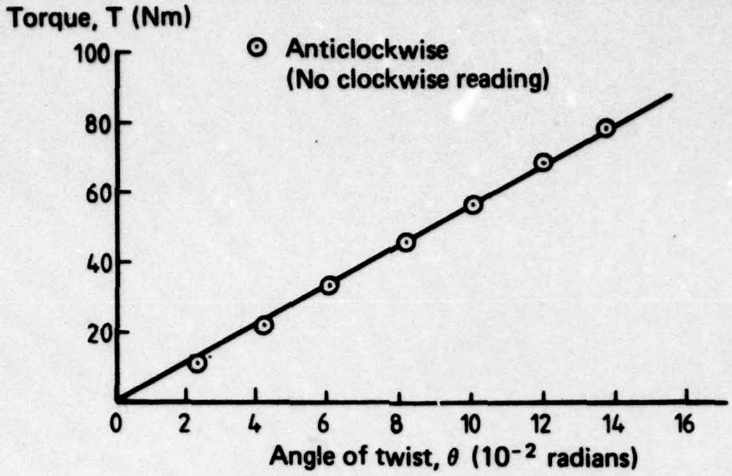
FIG. 16. CIRCUMFERENTIAL STRAIN IN 3-LAYER + 30°/– 30°/90° TUBE DURING FOAM FILLING

(b) *6-Layer Tube:*—The test runs are listed in Table 11 and the twist and strain measurements are shown in Fig. 17. The tube buckled elastically at a clockwise torque of 135 Nm and at an anticlockwise torque of 151 Nm. As already mentioned, an attempt at foam-filling this tube was unsuccessful.

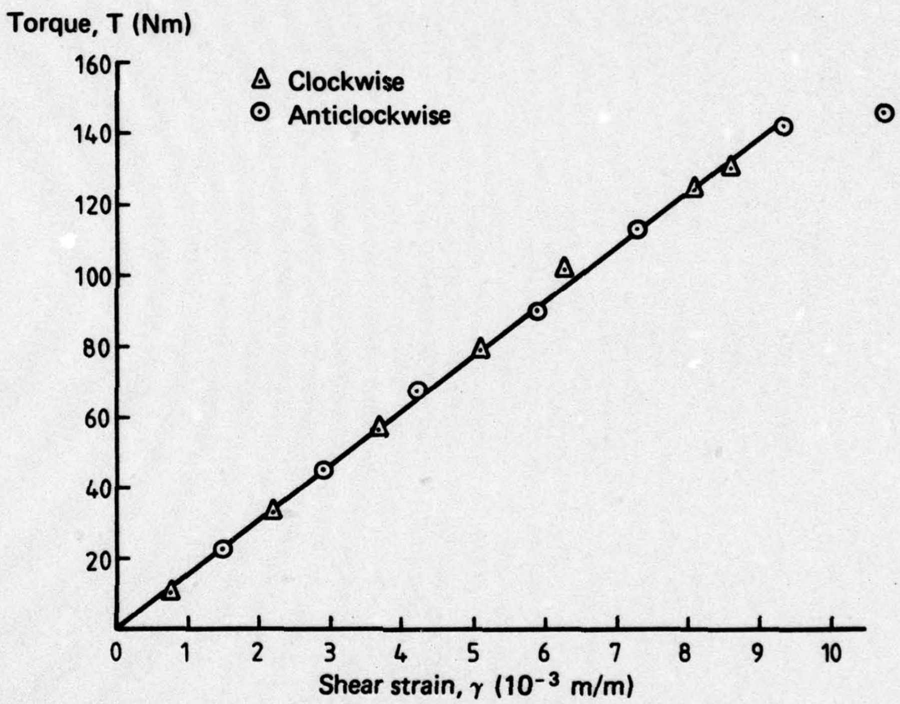
TABLE 11

Loading Runs for 6-Layer +30°/−30°/90° Tube

Run No.	Sense of Torque	Maximum Torque Applied (Nm)	Whether Failure Occurred	Comments on Failure
1	C	61	No	
2	A	135	No	
3	C	135	Yes	Elastic buckling
4	A	151	Yes	Elastic buckling



(a) Torque vs (total) angle of twist



(b) Torque vs shear strain

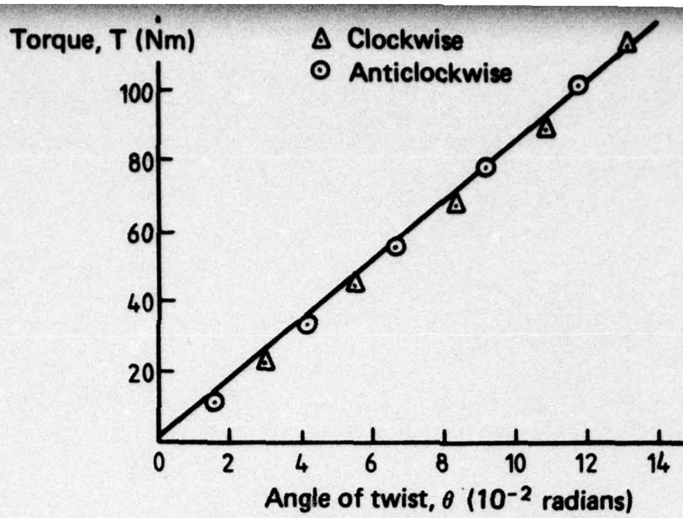
FIG. 17. DEFLECTIONS AND STRAINS FOR 6-LAYER + 30°/– 30°/90° TUBE

(c) *9-Layer Tube:*—As noted in Table 12, this tube underwent a material failure at a torque of 318 Nm. Deflection and strain data are shown in Fig. 18 and the failed tube itself is shown in Fig. 19.

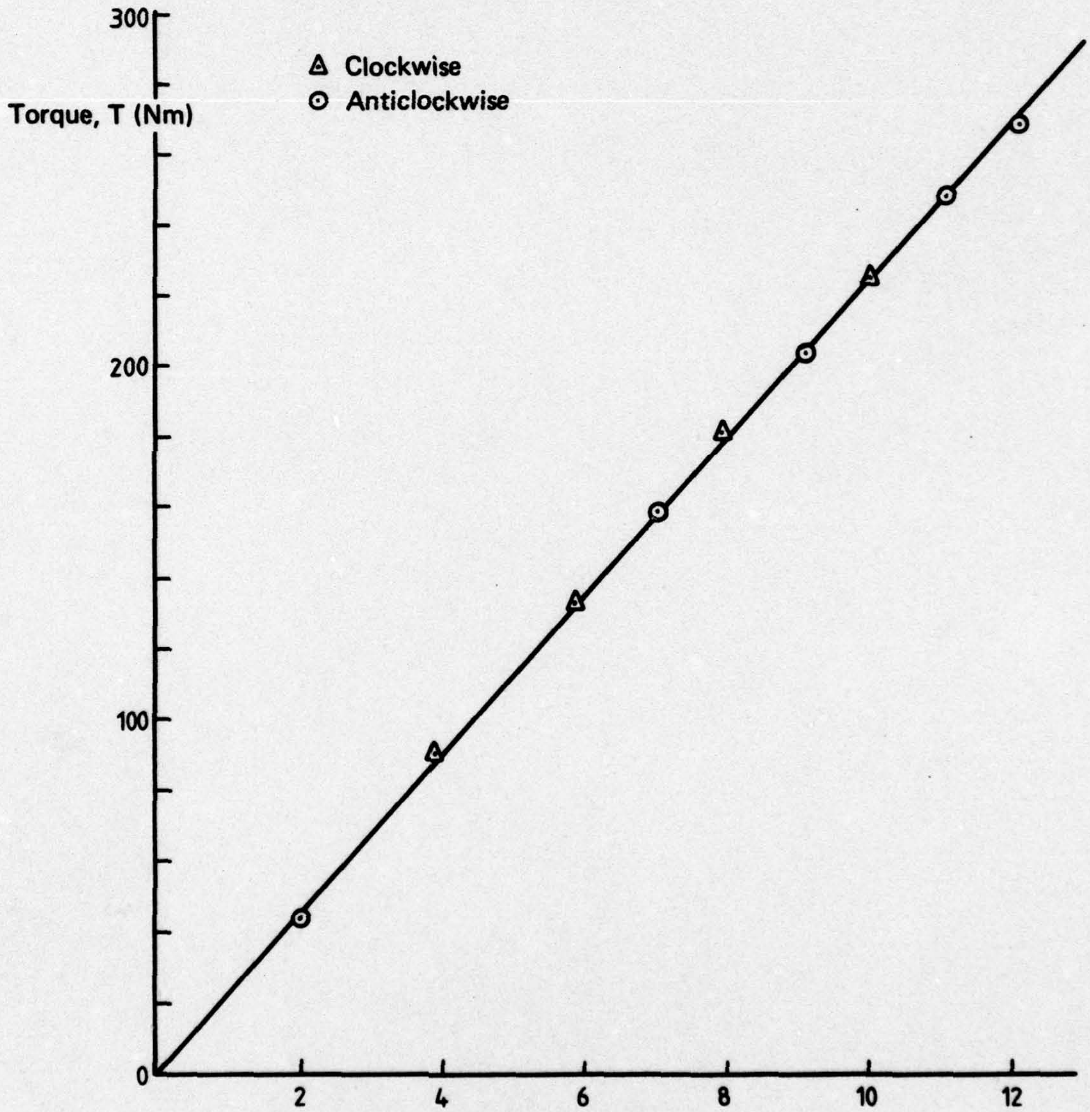
TABLE 12

Loading Runs for 9-Layer +30°/−30°/90° Tube

Run No.	Sense of Torque	Maximum Torque Applied (Nm)	Whether Failure Occurred	Comments on Failure
1	C	113	No	
2	A	113	No	
3	C	181	No	
4	A	226	No	
5	C	226	No	
6	A	318	Yes	Material failure



(a) Torque vs (total) angle of twist



(b) Torque vs shear strain

FIG. 18. DEFLECTIONS AND STRAINS FOR 9-LAYER + 30°/– 30°/90° TUBE

FIG. 19. MATERIAL FAILURE IN 9-LAYER + 30°/– 30°/90° TUBE

(d) *12-Layer Tube:*—The loading runs are listed in Table 13 and the deflection and strain data are shown in Fig. 20. This tube underwent a material failure at a torque of 498 Nm. The failure was unusual, in that it was of an "explosive" type with the tube fragmenting (Fig. 21).

TABLE 13

Loading Runs for 12-Layer +30°/−30°/90° Tube

Run No.	Sense of Torque	Maximum Torque Applied (Nm)	Whether Failure Occurred	Comments on Failure
1	A	226	No	
2	C	226	No	
3	A	339	No	
4	C	498	Yes	Material failure

(e) *18-Layer Tube:*—As can be seen from Table 14, a specimen failure was achieved here on a shortened length of tube, only after a series of failures in the end fittings; the material failure occurred at a torque of 893 Nm. Twist and strain data are shown in Fig. 22. Although these strains vary linearly with torque another strain gauge on the inside of the tube gave a markedly non-linear strain variation. Because of this the tube was sectioned and it was observed that quite large delaminations were present (Fig. 23).

TABLE 14

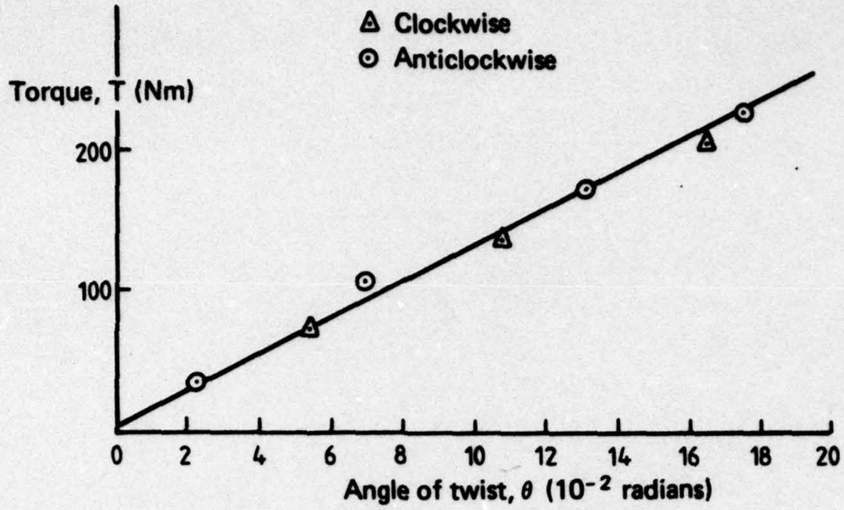
Loading Runs for 18-Layer +30°/−30°/90° Tube

Run No.	Sense of Torque	Maximum Torque Applied (Nm)	Whether Failure Occurred	Comments on Failure
1	A	226	No	
2	C	226	No	
3	A	509	No	
4	C	882	Yes	Glue failure in end fitting
5	C	735	Yes	Failure from pin-hole
6*	—	780	Yes	Glue failure in end fitting
7*	—	893	Yes	Material failure

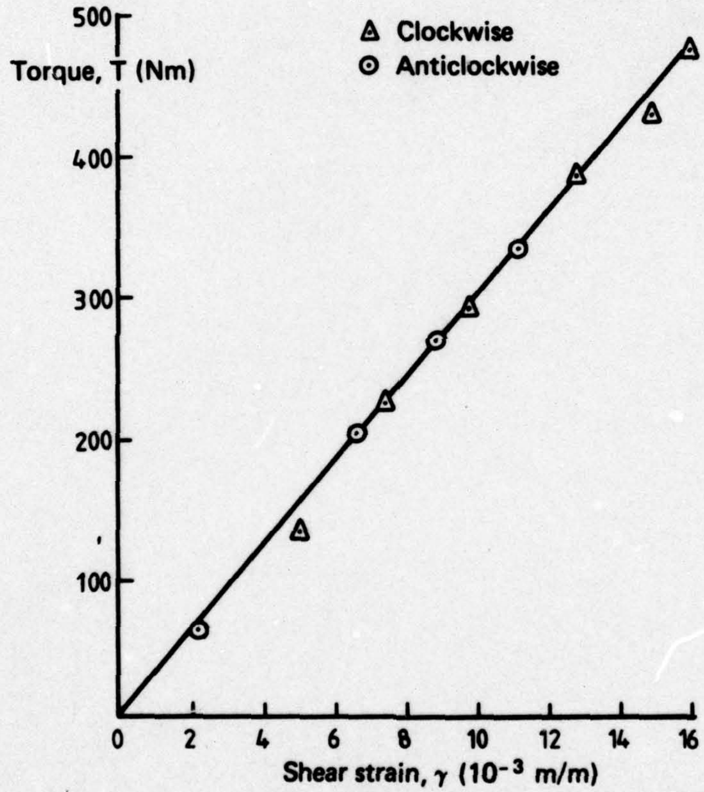
* Tests on shortened specimen

4.3 Young's Modulus and Poisson's Ratio Measurements

As well as the torque tests already described, axial load tests (tension or compression) were carried out on the tubes to measure the longitudinal Young's modulus and the associated Poisson's ratio. These tests had not been planned originally and, for the +45°/−45° tubes, specimens were generally obtained by salvaging a relatively short length (typically 120 mm) from a tube after the torsion programme had been completed. However, for the +30°/−30°/90° tubes, these modulus tests were done prior to any torsion failure and the complete tube length was used. Strain gauges were positioned on the outer surface of a tube to measure the longitudinal and transverse strains. The results are shown in Table 15.



(a) Torque vs (total) angle of twist



(b) Torque vs shear strain

FIG. 20 DEFLECTIONS AND STRAINS FOR 12-LAYER + 30°/– 30°/90° TUBE

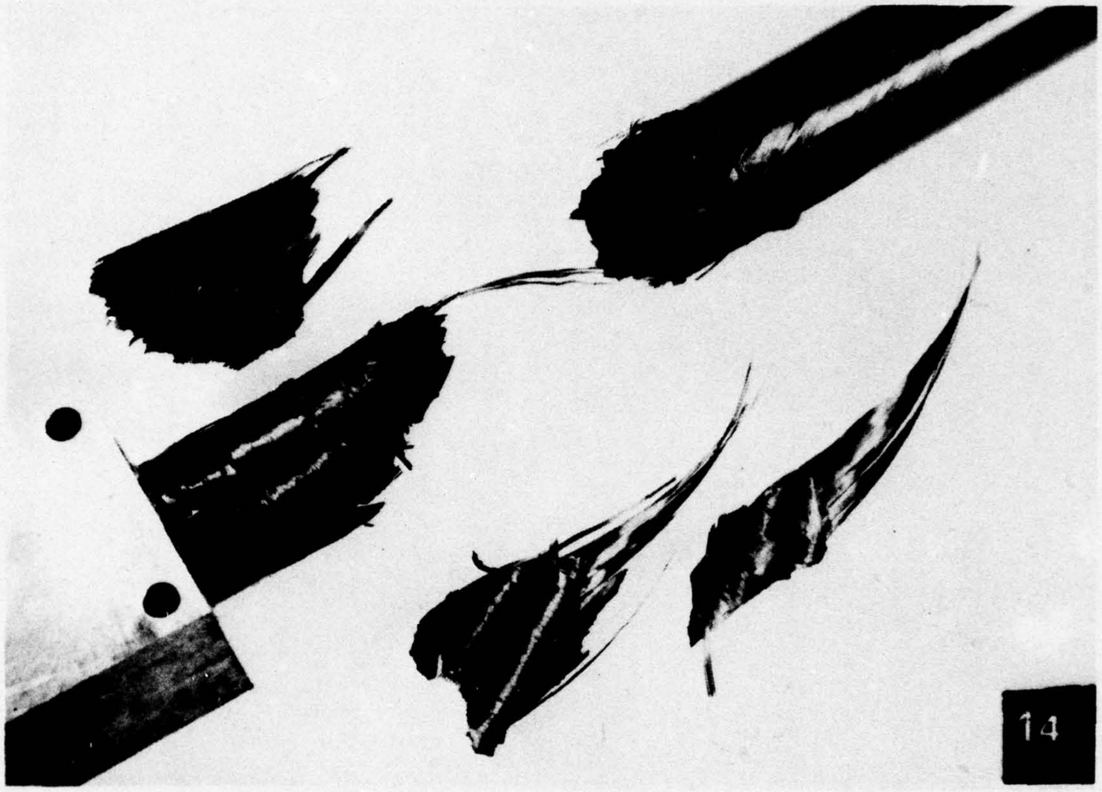
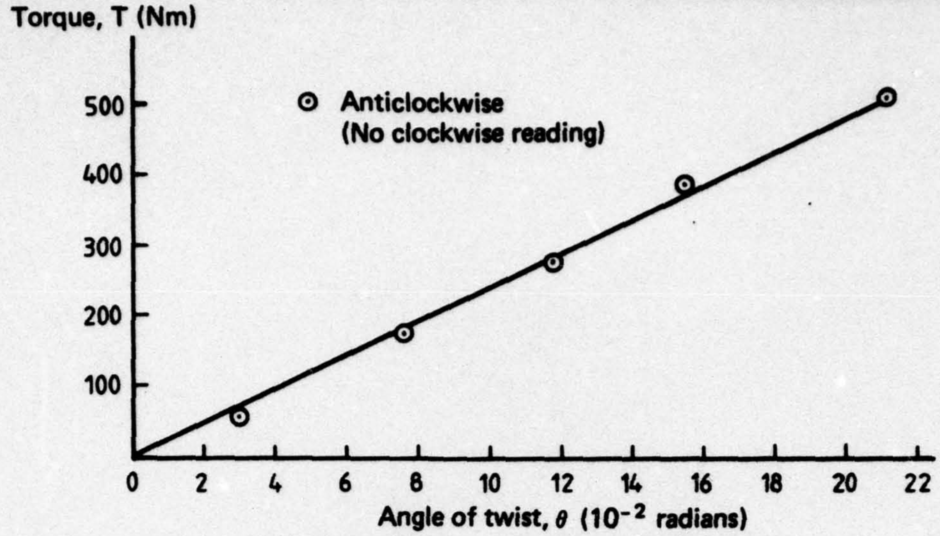
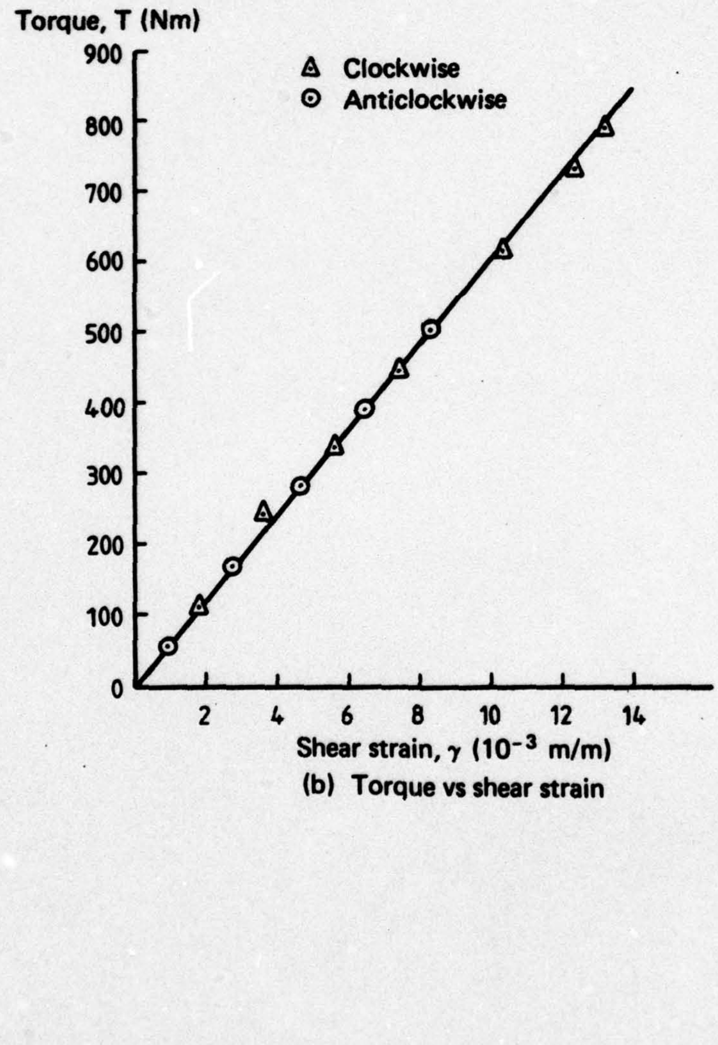


FIG. 21. MATERIAL FAILURE (OF EXPLOSIVE TYPE) IN 12-LAYER + 30°/- 30°/90° TUBE



(a) Torque vs (total) angle of twist



(b) Torque vs shear strain

FIG. 22. DEFLECTIONS AND STRAINS FOR 18-LAYER + 30°/– 30°/90° TUBE

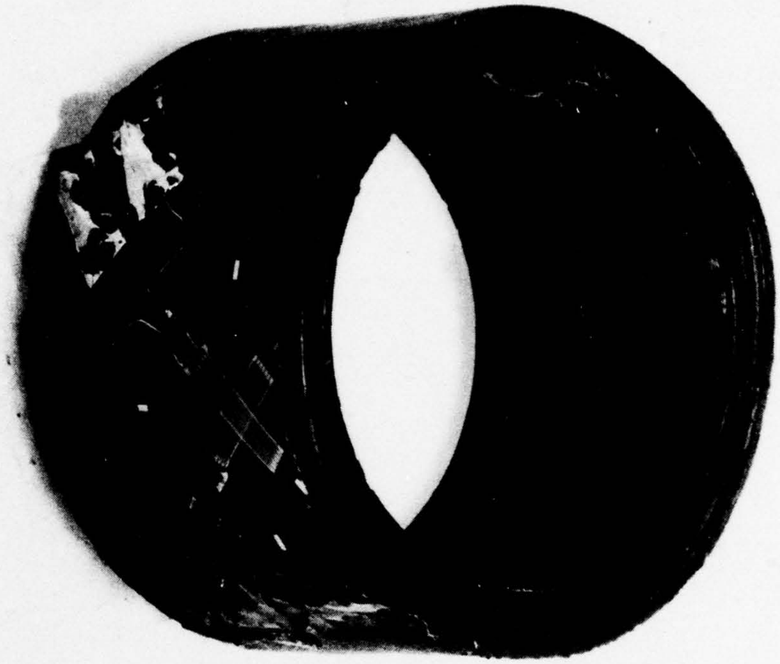


FIG. 23. DELAMINATIONS IN 18-LAYER + 30°/– 30°/90° TUBE

TABLE 15

Measured Values of Longitudinal Young's Modulus, E_L, and Associated Poisson's Ratio, ν_L, for Tubes

(*a*) +45°/−45° Tubes

Tube	Tension Test		Compression Test	
	E_L (G Pa)	ν_L	E_L (G Pa)	ν_L
4-Layer	11·3	0·81	11·5	0·76
6-Layer	12·5	0·61	12·2	0·61
8-Layer	12·6	0·70	13·3	0·69
12-Layer	13·9	0·89	13·8	0·85
16-Layer	14·5	0·63	14·5	0·64

(*b*) +30°/−30°/90° Tubes

Tube	Tension Test	
	E_L (G Pa)	ν_L
3-Layer	35·2	0·48
6-Layer	37·7	0·29
9-Layer	40·0	0·35
12-Layer	38·9	0·42
18-Layer	—	—

5. COMPARISON OF THEORY AND EXPERIMENT

5.1 General

The theoretical treatment of a composite structure in which exact account is taken of its anisotropic and heterogeneous character is often quite complicated, even for a structure as simple as a tube. Here, only approximate formulae, such as might be used at a preliminary design stage, are employed to provide theoretical results which can be compared with the experimental ones. For example, one frequently-used simplifying procedure will be to ignore the heterogeneous character of a tube (associated with different layers having different elastic properties) and to consider, instead, a homogeneous tube.

5.2 Elastic Moduli

(a) *Theoretical Moduli:*—Given the elastic moduli for the basic ply, the moduli for any laminate built up from it can, in principle, be calculated from standard formulae[7, 8]. However, this presupposes that

(i) the same fibre volume fraction is achieved in the laminate as in the test specimens from which the basic ply data were derived,

(ii) the laminate is symmetric about its mid-thickness plane, else the situation is complicated by bending effects.

Moduli for a 67% volume fraction basic ply have been given in Section 2.1 above but, as remarked in Section 2.4, it was considered that a volume fraction of only 50% was achieved in the tubes. Thus, it was necessary to modify the data of Section 2.1 before calculating the laminate moduli. This was done simply by reducing the Young's moduli E_1 and E_2 in the ratio 50/67. As far as the longitudinal modulus goes, this is in accord with generally accepted theory; use of the same procedure for the transverse modulus is more questionable but this quantity, being small, is of less importance. The other quantities ν_1, ν_2 and G_{12} were left unaltered. The basic ply moduli used in the calculations were, thus, as shown below:

$$E_1 = 100\text{ GPa} \qquad E_2 = 7 \cdot 5\text{ GPa}$$
$$\nu_1 = 0 \cdot 30 \qquad \nu_2 = 0 \cdot 02$$
$$G_{12} = 6\text{ GPa}$$

With these data, calculations of moduli were made for laminates comprising

(i) equal numbers of +45° and −45° layers (which is the situation for all the +45°/−45° tubes, save the 6-layer one),

(ii) twice as many +45° layers as −45° layers (which is the situation for the 6-layer tube),

(iii) equal numbers of +30°, −30° and 90° layers (which is the situation for all the +30°/−30°/90° tubes).

The results are shown in Table 16.

7. Bishop, S. M. Elastic Constants of Laminated Carbon Fibre Composite Plates. RAE TR 73182, 1974.

8. Hoskin, B. C. and Green, B. Stress Distributions in Fibre Reinforced Plastic Laminates under Simple Loadings. ARL SM Note 396, 1973.

TABLE 16
Theoretical Moduli for Laminates

Quantity	Laminate Pattern		
	1@ +45° 1@ −45°	2@ +45° 1@ −45°	1@ +30° 1@ −30° 1@ 90°
E_L (G Pa)	19·8	19·5	40·8
ν_L	0·65	0·62	0·28
E_T (G Pa)	19·8	19·5	40·8
ν_T	0·65	0·62	0·28
G_{LT} (G Pa)	25·9	23·8	16·0

(b) *Shear Modulus:*—Two independent estimates for the shear modulus of a tube are provided by the twist and the strain gauge data. In each case the derivation of the modulus from the data is here based on the assumption that a tube behaves as a homogeneous, orthotropic material with an axis of orthotropy in the direction of the longitudinal axis of the tube. Then the situation is essentially the same as for an isotropic tube, the following formulae applying[9]:

$$T = G_{LT}\, I_p\, \theta/l \tag{2}$$

$$T = G_{LT}\, I_p\, \gamma/r_o \tag{3}$$

where T is the torque,

θ is the angle of twist over a length l,

γ is shear strain on the outer surface,

I_p is the polar moment, viz. $(\pi/2)\,(r_o^4 - r_i^4)$,

r_i, r_o are the inner and outer radii, respectively.

The twist data can be used with eqn (2) and the strain data with eqn (3) to evaluate a shear modulus G_{LT}. In each case the data were fitted to a "least-squares" straight line through the origin, the clockwise and anti-clockwise results being treated separately. (Not all the data points have been shown in the Figures of Section 4, above.) The results are given in Tables 17 and 18.

Considering first the +45°/−45° tubes, it must be borne in mind that application of the above procedure to the 6-layer tube is suspect because the tube is not orthotropic. Excluding that tube (although the results for it do not differ significantly), the results for the remainder can be summarised as follows:

Theoretical value of shear modulus	=	25·9 GPa
Mean test value from twist data	=	22·0 GPa
Mean test value from strain data	=	21·5 GPa

Thus, whilst the test values are reasonably consistent with each other, their joint mean is 16% less than the theoretical value.

In the comparison of theory and experiment for the +30°/−30°/90° tubes, the test results

9. Lekhnitskii, S. G. Theory of Elasticity of an Anisotropic Elastic Body (translated by P. Fern). Holden-Day, San Francisco, 1963 pp. 265–268.

TABLE 17

Value of Shear Modulus from Twist Data

(*a*) +45°/−45° Tubes

Tube	I_p	l	Clockwise		Anticlockwise	
			T/θ	G_{LT}	T/θ	G_{LT}
	(10^{-9} m^4)	(m)	(Nm/rad)	(G Pa)	(Nm/rad)	(G Pa)
4-Layer	9·63	0·362	595	22·4	597	22·4
6-Layer	16·7	0·372	964	21·5	1001	22·3
8-Layer	24·5	0·363	1449	21·4	1548	22·9
12-Layer	39·3	0·360	2308	21·2	2411	22·1
16-Layer	55·2	0·361	—	—	3266	21·4

(*b*) +30°/−30°/90° Tubes

Tube	I_p	l	Clockwise		Anticlockwise	
			T/θ	G_{LT}	T/θ	G_{LT}
	(10^{-9} m^4)	(m)	(Nm/rad)	(G Pa)	(Nm/rad)	(G Pa)
3-Layer	8·51	0·349	233	9·6	276	11·3
6-Layer	15·5	0·363	—	—	569	13·3
9-Layer	22·9	0·359	832	13·0	860	13·5
12-Layer	33·5	0·356	1235	13·1	1303	13·9
18-Layer	63·8	0·356	—	—	2384	13·3

TABLE 18

Values of Shear Modulus from Strain Data

(*a*) +45°/−45° Tubes

Tube	Clockwise		Anticlockwise		Foam-Filled	
	T/γ (10^4 Nm)	G_{LT} (G Pa)	T/γ (10^4 Nm)	G_{LT} (G Pa)	T/γ (10^4 Nm)	G_{LT} (G Pa)
4-Layer	1·40	19·4	1·47	20·4	1·49	20·6
6-Layer	2·53	21·0	2·60	21·6	2·54	21·1
8-Layer	3·89	22·7	3·93	22·9	—	—
12-Layer	5·55	21·2	5·59	21·4	—	—
16-Layer	7·77	22·1	7·89	22·5	—	—

(*b*) +30°/−30°/90° Tubes

Tube	Clockwise		Anticlockwise		Foam-Filled	
	T/γ (10^4 Nm)	G_{LT} (G Pa)	T/γ (10^4 Nm)	G_{LT} (G Pa)	T/γ (10^4 Nm)	G_{LT} (G Pa)
3-Layer	0·71	11·1	0·72	11·3	0·82	12·8
6-Layer	1·53	13·6	1·55	13·7	—	—
9-Layer	2·28	14·1	2·23	13·8	—	—
12-Layer	3·01	13·3	3·05	13·4	—	—
18-Layer	6·04	15·2	6·10	15·4	—	—

for the 3-layer and 9-layer tubes will be excluded because the laminates here are not symmetric about the mid-thickness plane. The results can then be summarised as follows:

Theoretical value of shear modulus = 16·0 GPa
Mean test value from twist data = 13·4 GPa
Mean test value from strain data = 14·1 GPa

Here the joint mean of the test values is 14% less than the theoretical value.

Reference to Tables 17 and 18 shows that there is relatively little difference between the modulus values for a clockwise and an anti-clockwise torque. Also, for the two +45°/−45° tubes foam-filling did not alter the shear modulus significantly; however, for the +30°/−30°/90° tube it increased the modulus by around 15%.

(c) *Young's Modulus and Poisson's Ratio:*—The measured values for the longitudinal Young's modulus and associated Poisson's ratio have already been given in Table 15 of Section 4.3. Using the same specimens as in (b) above, the results for the +45°/−45° tubes may be summarised as follows:

Theoretical value of longitudinal Young's modulus = 19·8 GPa
Mean test value = 13·2 GPa
Theoretical value of associated Poisson's ratio = 0·65
Mean test value = 0·75

The experimental modulus value here differs from the theoretical one by 33%.

Much better agreement was obtained with the +30°/−30°/90° tubes, the analogous results being:

Theoretical value of longitudinal Young's modulus = 40·8 GPa
Mean test value = 38·3 GPa
Theoretical value of associated Poisson's ratio = 0·28
Mean test value = 0·36

5.3 Buckling Failures

Theoretical formulae for the torsional buckling of tubes of homogeneous orthotropic material, where one of the axes of orthotropy is parallel to a tube axis, have been given by Hayashi[10]. These formulae were used by Cervelli (ref. 1) in work on GFRP tubes and showed good agreement with experiment. The same formulae will be used here.

Assuming "clamped ends", the calculation proceeds as follows. First, a number, N, defined by

$$N = (1/7\cdot8)\,(L/d)^2 \sqrt{\{E_L/(1-\nu_L\nu_T)\,E_T\}} \tag{4}$$

is calculated. Then, depending on whether the ratio of tube (mean) diameter, d, to wall thickness, t, does or does not exceed N different formulae for the buckling shear stress, τ_b, apply:

(i) $d/t > N$,

$$\tau_b = \{E_T/(1-\nu_L\nu_T)\}\,(d/L)^2\,(t/d)^2\,\{4\cdot6 + \sqrt{(7\cdot8 + 1\cdot67\,H^{3/2})}\} \tag{5}$$

where

$$H = (L/d)^2(d/t)\sqrt{\{(1-\nu_L\nu_T)\,E_L/E_T\}} \tag{6}$$

(ii) $d/t < N$

$$\tau_b = 0\cdot77\,(t/d)^{3/2}E_L^{1/4}\,E_T^{3/4}/(1-\nu_L\nu_T)^{3/4} \tag{7}$$

The associated critical value of the torque as given by thin tube theory is

$$T_b = (\pi d^2/2)\,t\,\tau_b \tag{8}$$

Values of the buckling torque have been calculated from the above formulae, using both the theoretical moduli of Table 16 and the experimentally determined moduli of Table 15. (For

10. Hayashi, T. Torsional Buckling of Orthogonal-Anisotropic Cylinders. Proceedings of Eighth International Congress of Theoretical and Applied Mechanics, Istanbul, 1952, pp. 189–190.

the $+45°/-45°$ tubes the mean of the tension and compression test values was taken. Also, it was assumed that $E_T = E_L$ and $\nu_T = \nu_L$). The results are shown in Table 19 along with the torques achieved in the tests.

TABLE 19

Comparison of Theoretical and Experimental Values of Buckling Torque

(*a*) $+45°/-45°$ Tubes

Tube	Theoretical Torque		Experimental Torque	
	Using Calculated Moduli (Nm)	Using Measured Moduli (Nm)	Clockwise (Nm)	Anticlockwise (Nm)
4-Layer	74·5	57	48	73·5
6-Layer	242	152	149	200

(*b*) $+30°/-30°/90°$ Tubes

Tube	Theoretical Torque		Experimental Torque	
	Using Calculated Moduli (Nm)	Using Measured Moduli (Nm)	Clockwise (Nm)	Anticlockwise (Nm)
3-Layer	90	86	25	21
6-Layer	317	295	135	151

Meaningful comparisons between theory and experiment are difficult, firstly because of the substantial differences between the "clockwise" and "anticlockwise" torques and, secondly, because of the uncertainties in appropriate moduli values. In the case of the $+45°/-45°$ tubes the various values at least span similar ranges. (Again it must be borne in mind that the 6-layer tube is not orthotropic.) For the $+30°/-30°/90°$ tubes, the theoretical formula gives values grossly in excess of those achieved in the tests. It might be noted that the theoretical critical torque for the 6-layer $+30°/-30°/90°$ tube is significantly larger than that for the 6-layer $+45°/-45°$ one, which was a main reason for investigating the former lay-up; however, the test torque is smaller.

5.4 Material Failures

Strength theories for composite structures are still very much in the developing stage; some such theories are quite complex and require a considerable amount of input data to be utilised.[11] The simplest theory, and the one which requires the minimum amount of input data is the so-called netting analysis[12]. Here, given the strength of the basic ply under uniaxial loads in the fibre direction, the strength of a laminated structure can be predicted. This theory will be used to obtain values which can be compared with the experimental values of torque producing material failures.

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11. Tsai, S. W. and Wu, E. M. A General Theory of Strength for Anisotropic Materials. Journal of Composite Materials, vol. 5, 1971, pp. 55–80.

12. Harris, G. Z. Optimum Fibre Arrangements for Reinforced Sheets under Combined Loading. ARC CP 975, Aeronautical Research Council, London, 1968.

It can be readily established from a netting analysis that the critical shear stress, τ_m, for the present laminate patterns is given by the following formulae:

(i) $+45°/-45°$ laminate with equal numbers of each orientation

$$\tau_m = F_1/2 \tag{9}$$

(ii) $+45°/-45°$ laminate with "2 @ + 45°, 1 @ −45°"

$$\tau_m = F_1/3 \tag{9a}$$

(iii) $+30°/-30°/90°$ laminate,

$$\tau_m = F_1/(2\sqrt{3}) \tag{10}$$

where F_1 is the uniaxial strength of the basic ply. Since the maximum stress is attained on the outer surface of a tube, the associated critical value of the torque, T_m, is given by

$$T_m = I_p\,\tau_m/r_o \tag{11}$$

For the present calculations the value of F_1 was obtained by reducing the value of 1120 MPa, quoted in Section 2.1 for a 67% volume fraction ply, in the ratio 50/67 i.e., here $F_1 = 836$ MPa. (Strictly, F_1 should be taken as the smaller of the tensile and compressive strengths of the basic ply but only the former was available; in some cases, there can be significant differences between the two strengths.)

Comparisons of theory and experiment are shown in Table 20. (For tubes which originally failed by buckling, the comparison is made for the foam-filled configuration). It can be seen that the agreement is generally poor for the $+45°/-45°$ tubes, the experimental values always being less than the theoretical ones and, sometimes, grossly so. Somewhat better agreement was achieved for the thicker tubes of the $+30°/-30°/90°$ series.

TABLE 20

Comparison of Theoretical (Netting Analysis) and Experimental Values of Torque for Material Failure

(*a*) $+45°/-45°$ Tubes

Tube	Theoretical Torque (Nm)	Experimental Torque (Nm)
4-Layer	300	96*
6-Layer	337	262*
8-Layer	716	294
12-Layer	1095	675
16-Layer	1470	>950**

(*b*) $+30°/-30°/90°$ Tubes

Tube	Theoretical Torque (Nm)	Experimental Torque (Nm)
3-Layer	154	70·5*
6-Layer	271	—
9-Layer	389	318
12-Layer	546	498
18-Layer	955	893

* Test value for foam-filled tube

** Based on second tube tested.

6. DISCUSSION

6.1 Test Procedures

The main difficulty arising in the tests themselves was that of obtaining a satisfactory glued joint in the end-fittings. Whilst a torque of 1333 Nm had been satisfactorily transmitted in a trial specimen, apparently similar joints in the main programme failed at much lower torques e.g., around 800 Nm. The reason for this reduced performance was not definitely established, but difficulty in obtaining a uniform glue thickness (especially for tubes that had diametral variations) was seen as a possible factor. Attempts at improving the strength of a joint by the insertion of drive-pins were generally unsuccessful due to material failures originating at the pin-holes.

Only one of the test specimens was replicated, namely, the 16-layer $+45°/-45°$ tube. In fact, three such specimens were tested, namely, the trial tube ($T_m = 1333$ Nm), the first main specimen ($T_m = 845$ Nm) and the second main specimen ($T_m > 950$ Nm). No cause was definitely established for the variation in performance of these three specimens. However, it was noted that several of the tubes had local areas of "fibre-waviness" which would degrade performance. (See, again, Fig. 9.)

Variability in the performance of FRP structures is fairly common and, in retrospect, it is clear that replication of all tests would have been most desirable.

6.2 Modulus Measurements

For tubes with laminate patterns which were orthotropic and symmetric about the mid-thickness plane, the measured values of shear modulus showed a fair agreement with theoretical values calculated from laminate theory; the measured values were, typically, 15% below the theoretical ones.

Measured values of Young's modulus for the tubes showed good agreement with theoretical ones when the tests were carried out on long tubes; this was the case for the $+30°/-30°/90°$ tubes where L/d was 15. However, in tests on shorter tubes with L/d around 5, which was the case for the modulus tests on the $-45°/+45°$ specimens, the measured values were much smaller than the theoretical ones; also, they showed a steady increase with tube wall thickness. It is known that there are potential difficulties in obtaining uniform strain distributions in short-length composite tubes[13, 14]. However, a "rule-of-thumb" that a satisfactory minimum specimen length, l_s, is given by (ref. 13)

$$l_s = 2d + l_g$$

where l_g is the gauge length, was fulfilled here.

Of course, the $+45°/-45°$ specimens were all salvaged from tubes already tested to failure and some damage may have occurred to them, although none was apparent. Moreover, the fact that the measured modulus steadily increases with tube wall thickness indicates a more systematic effect being present. For the above reasons, there are some doubts about the validity of the measured Young's modulus values for the $+45°/-45°$ tubes.

6.3 Torsion Buckling

The most important observation on the torsional buckling failures was the significant difference between the critical torques in the "clockwise" and "anticlockwise" senses. Until now these terms have only been used descriptively. However, in Fig. 24 are shown those directions of the shear stresses acting on elements of the tubes corresponding to that sense of torque which gives the higher buckling load; also shown is the direction of the fibres in the outermost layer

13. Pagano, N. J. and Whitney, J. M. Geometric Design of Composite Cylindrical Characterization Specimens,J. Comp. Mat. vol. 4, 1970. pp. 360–378.

14. Whitney, J. M., Pagano, N. J. and Pipes, R. B. Design and Fabrication of Tubular Specimens for Composite Characterization, pp. 52–67 of "Composite Materials: Testing and Design (Second Conference)", ASTM STP 497, 1972.

of a tube. Considering the shear stress as resolved into equivalent tension and compression stresses, it can be seen that in all cases the tubes are stronger with respect to buckling when the sense of the torque is such that the fibres in the outermost layer are either exactly (for the $+45°/-45°$ tubes) or approximately (for the $+30°/-30°/90°$ tubes) in the direction of the equivalent compression. This sense dependence of the buckling strength of torque tubes has also been observed by Marlowe *et al.* (ref. 6) and the same correlation with fibre direction was noted. (Probably the 6-layer $+45°/-45°$ tube of the present programme cannot be regarded as satisfactory evidence on this point because of the biassed nature of the lay-up, but the effect is certainly present in the other tubes.)

According to Marlowe *et al.*, the above effect is predicted by a theoretical analysis of Chao[15]. The relatively simple theoretical analysis of the present paper is based on the assumption of a homogeneous orthotropic tube and, consequently, is incapable of predicting such an effect. Clearly it is important to be aware of the possibility of this effect when proof-testing torque tubes.

The foam-filling procedure would seem to be a convenient way of substantially up-grading the performance of an existing tube which fails by torsional buckling and which, for some reason, cannot have its wall thickness increased.

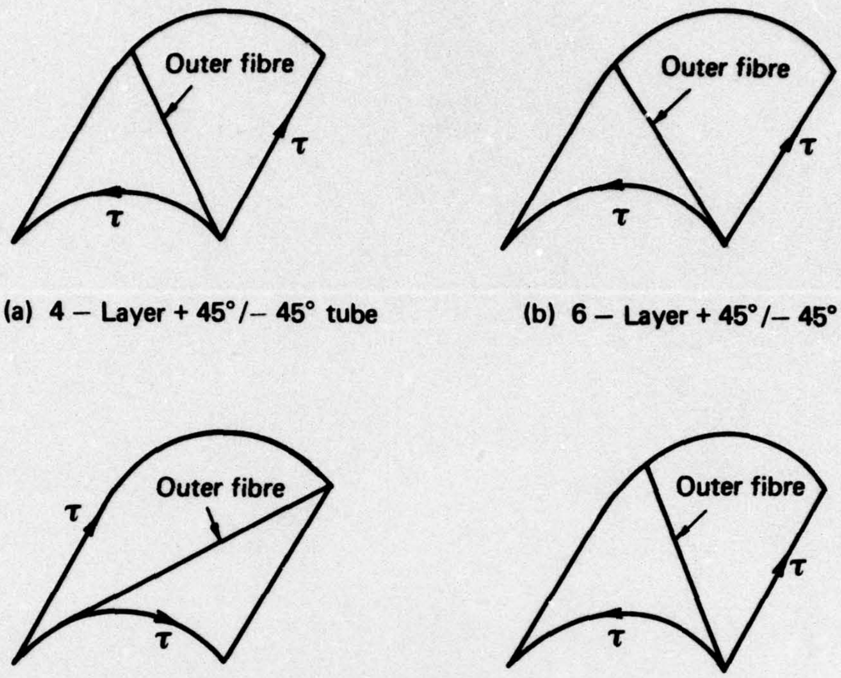
6.4 Material Failures

In predicting material failure, the netting analysis grossly over-estimated the strength in the case of two of the three foam-filled tubes and the 8-layer $+45°/-45°$ one. For the former tubes, the situation at failure might be quite complex; although it appeared that all buckling had been suppressed it is conceivable that, locally, the support given by the foam might have broken down, leading to failure before the shear strength of a tube was reached. The 8-layer $+45°/-45°$ tube was not considered a very satisfactory specimen because of the relatively extensive "fibre-waviness" (Fig. 9); in fact, it sustained a torque only 12% greater than the 6-layer tube (in the foam-filled condition). The variability in performance amongst the three 16-layer $+45°/-45°$ specimens has already been alluded to. For the above reasons, it is difficult to draw any conclusions about the value of a netting analysis.

6.5 Summary of Tube Performance

The test data for all tubes have been summarised in Figs. 25 and 26. There the nominal shear stress at failure, as calculated from eqn (11) using the test value of the failure torque, is plotted against the ratio d/t. (Included among the data is the value for the "trial" $+45°/-45°$ tube to which reference has been made more than once.)

15. Chao, T. L. Minimum Weight Design of Stiffened Fibre Composite Cylinders, AFML TR 69-251, 1969.



(a) 4 – Layer + 45°/– 45° tube

(b) 6 – Layer + 45°/– 45° tube

(c) 3 – Layer + 30°/ – 30°/90° tube

(d) 6 – Layer + 30°/– 30°/90° tube

FIG. 24. SHEAR STRESS (τ) ON TUBE ELEMENT GIVING HIGHER BUCKLING TORQUE AND CORRESPONDING DIRECTION OF OUTERMOST FIBRE

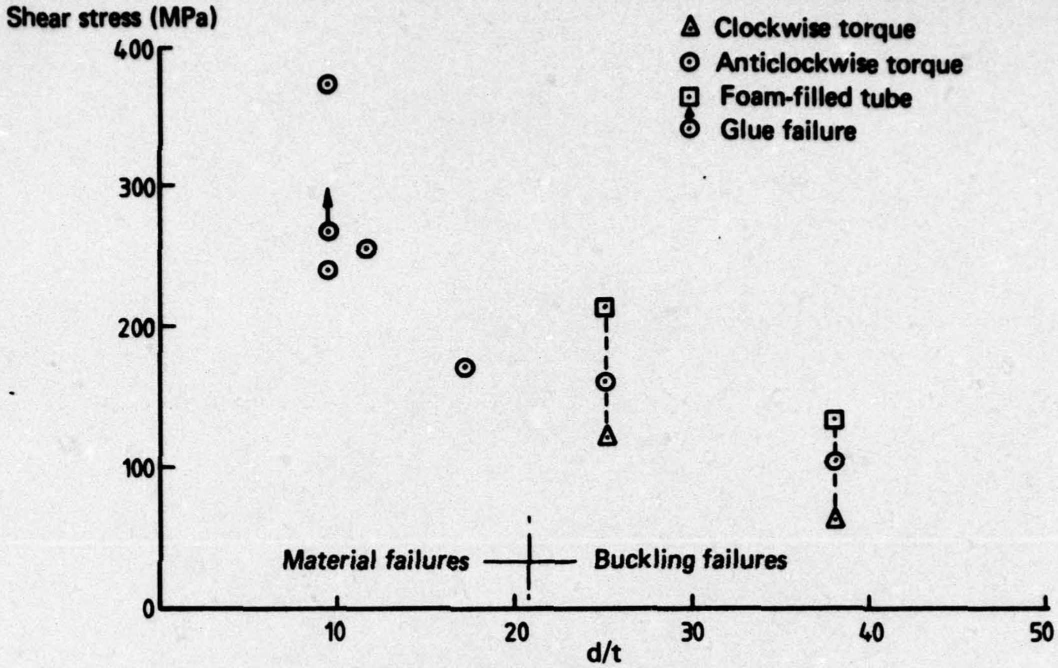


FIG. 25. TEST RESULTS FOR + 45°/– 45° TUBES

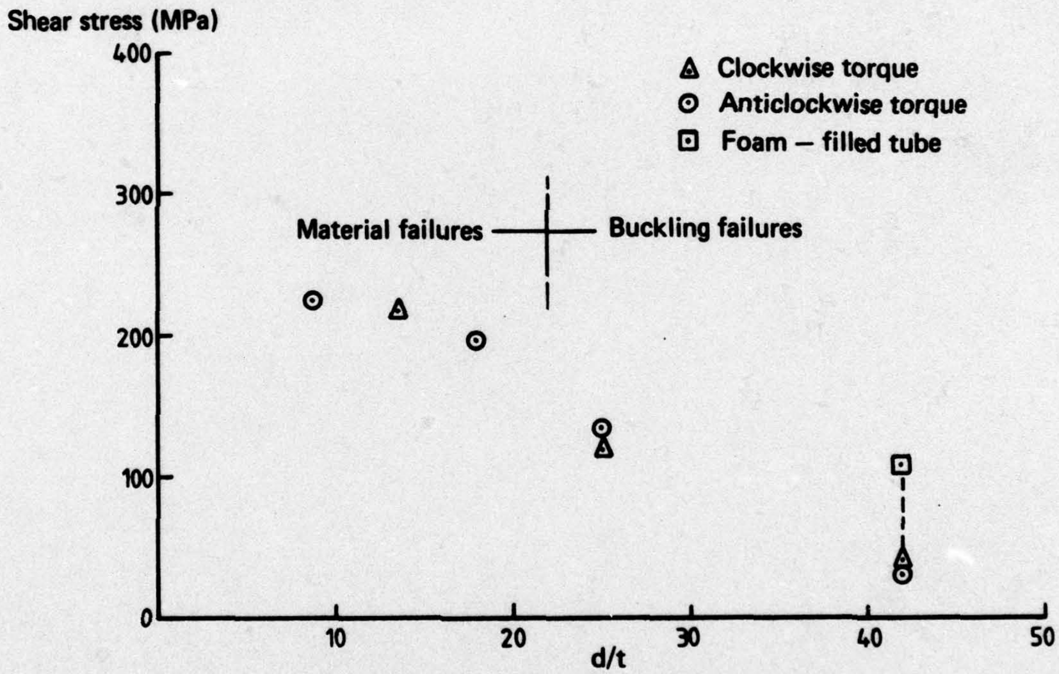


FIG. 26. TEST RESULTS FOR + 30°/– 30°/90° TUBES

7. CONCLUSIONS

A programme on the performance of CFRP torque tubes has been carried out. The following conclusions, some of a positive character, some of a negative character, have been drawn.

- (i) The torsional buckling of CFRP tubes is elastic in character and the tubes recover on unloading.
- (ii) The torsional buckling strength of such tubes can be markedly dependent on the sense of the torque.
- (iii) Filling a thin tube with a light-weight foam substantially improves its buckling performance.
- (iv) The theoretical formula for the torsional buckling stress given by Hayashi is moderately successful in predicting failure loads for tubes with a $+45°/-45°$ lay-up but grossly overestimates the strength of those with a $+30°/-30°/90°$ lay-up.
- (v) In the absence of buckling, the torque-strain behaviour is linear up to failure.
- (vi) There are substantial difficulties in obtaining a consistent performance from CFRP-to-metal glued joints. The use of pins as a means for the attempted improvement of the strength of such joints did not prove satisfactory here.
- (vii) There are difficulties in obtaining a consistent performance from CFRP structures themselves, as far as ultimate strength is concerned. Problems of fibre-waviness and unobserved delaminations can be important here. However, these problems should be soluble with improved production and inspection techniques.

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